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Mathematical modelling of the spread of contamination during fires in forests exposed to radioactive contamination

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Abstract.
The paper suggested in the context of the general mathematical model of forest fires [1] gives a new mathematical setting and method of numerical solution of a problem of a radioactive spread above the forest region. Numerical solution of problems of radioactive smoke spread during crown fire in exemplified heat energy release in the forest fire front was found. Heat energy release in the forest fire front was found to cause further radioactive particles spread by the action of wind. In the absence of wind, radioactive smoke particles deposit again on the underlying surface after a time. As a wind velocity increases, these particles are transferred in the ground layer over distances proportional to a wind velocity.

Introduction

The most intense and significant transfer of radionuclides to the forest area, exposed to radioactive contamination occurs as a result of the combined action of wind and forest fires [2-8]. Moreover, large forest fires are closely related to the vortex atmospheric phenomena. Large-scale forest fires, under appropriate conditions, generate a cloud of gas that generates atmospheric tornado, and the latter may intensify the spread of fire in mass due to increased flow of oxygen to the fire. That is, a firestorm, which supports the existence of the gas cloud and ensure that the products of combustion in these conditions. Thus, for mathematical modeling is necessary to formulate the problem of heat and mass transfer surface air with forest fires. Using the general mathematical model of forest fires [1], we can construct a model of the spread of radioactive contamination repeated as a result of wind and forest fires. In addition to physical and chemical factors that arise from forest fires must take into account the physical and chemical processes and the chemical components that arise during the radioactive decay of substances. In particular should be considered the dispersed radioactive particles containing uranium, plutonium, cesium and other radioactive chemicals. Experimental data suggest that as a result of radiolysis of forest fuel (FF) the rate of the drying and pyrolysis FF are reduced.

Physical and mathematical setting

Source separation of radionuclides in forest fires, is a source of heat and mass, located in a region of space [7]. Its temperature is determined by a function of time and coordinates. 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) the flow has a developed turbulent nature and molecular transfer is neglected; 3) 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; 4) the binary gas-dispersed mixture made of particles of condensed phase, including radioactive aerosols and gas phase - the components oxygen, inert gases and the combustible components. Let the coordinate reference point x_1, $x_2 = 0$ 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 upward (Figure 1).

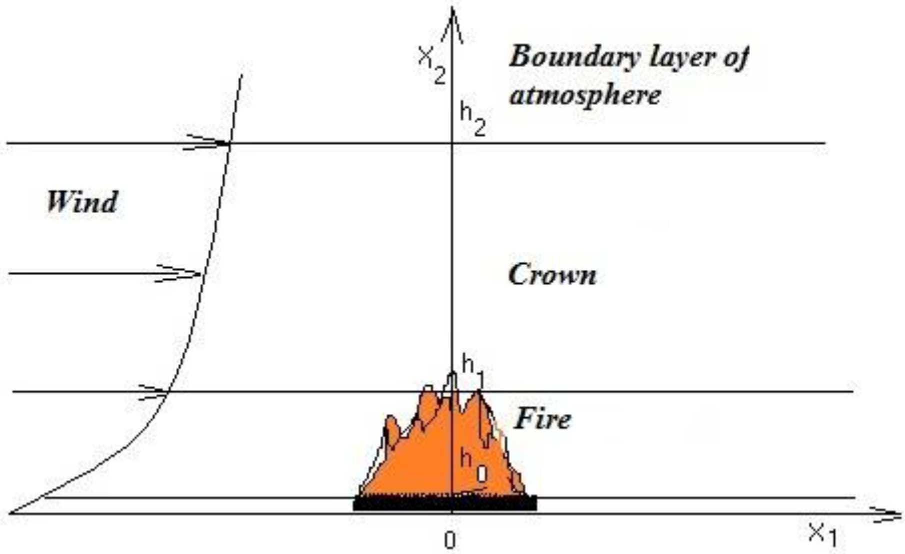

Figure 1.

For the atmospheric boundary layer stated above, the problem reduces to the solution of the following system of equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho v_j) = 0,\ j = 1,2,\ i = 1,2; \tag{1}$$

$$\rho \frac{dv_i}{dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(-\rho \overline{v_i' v_j'}) - \rho g_i; \tag{2}$$

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

$$\rho \frac{dc_\alpha}{dt} = \frac{\partial}{\partial x_j}(-\rho \overline{v_j' c_\alpha'}) + R_{5\alpha} - \dot{m} c_\alpha,\ \alpha = \overline{1,6}; \tag{4}$$

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

$$\sum_{\alpha=1}^{6} c_\alpha = 1,\ p_e = \rho R T \sum_{\alpha=1}^{6} \frac{c_\alpha}{M_\alpha}, \vec{v} = (v_1, v_2), \vec{g} = (0, g).$$

In the area located between the low level of roughness and upper boundary of forest canopy we have the system of equations averaged over the height of the canopy [1] expressing conservation laws for multiphase multicomponent reactive continuum:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_1}(\rho v_1)=Q-(\dot{m}^- - \dot{m}^+)/h; \tag{6}$$

$$\rho\frac{dv_i}{dt}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}(-\rho\overline{v_i'v_j'})-\rho s c_d v_i|\vec{v}|-\rho g_i - Qv_i+(\tau_i^- - \tau_i^+)/h,\ i=1,2; \tag{7}$$

$$\rho c_p\frac{dT}{dt}=\frac{\partial}{\partial x_1}(-\rho c_p v_1'\overline{T'})+q_5R_5-\alpha_v(T-T_s)+(q_T^- - q_T^+)/h+k_g(cU_R-4\sigma T^4); \tag{8}$$

$$\rho\frac{dc_\alpha}{dt}=\frac{\partial}{\partial x_1}(-\rho\overline{v_1'c_\alpha'})+R_{5\alpha}-\dot{m}c_\alpha+(J_\alpha^- - J_\alpha^+)/h,\ \alpha=\overline{1,6}; \tag{9}$$

$$\frac{\partial}{\partial x_1}\left(\frac{c}{3k}\frac{\partial U_R}{\partial x_1}\right)-kcU_R+4k_S\sigma T_S^4+4k_g\sigma T^4+(q_R^- - q_R^+)/h=0, k=k_g+k_S; \tag{10}$$

$$\sum_{i=1}^{4}\rho_i c_{pi}\phi_i\frac{\partial T_S}{\partial t}=q_3R_3-q_{2R_{2s}}+k_s(cU_R-4\sigma T_S^4)+\alpha_V(T-T_S)\ ; \tag{11}$$

$$\rho_1\frac{\partial\phi_1}{\partial t}=-R_1,\ \rho_2\frac{\partial\phi_2}{\partial t}=-R_2,\ \rho_3\frac{\partial\phi_3}{\partial t}=\alpha_C R_1-\frac{M_C}{M_1}R_3,\ \rho_4\frac{\partial\phi_4}{\partial t}=0\ ; \tag{12}$$

$$\sum_{\alpha=1}^{6}c_\alpha=1,\ p_e=\rho RT\sum_{\alpha=1}^{6}\frac{c_\alpha}{M_\alpha}\ ; \tag{13}$$

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

$$R_{51}=-R_3-\frac{M_1}{2M_2}R_5, R_{52}=\nu(1-\alpha_c)R_1-R_5, R_{54}=\alpha_6R_1, \tag{14}$$

$$R_{55}=\frac{\alpha_4\nu_2}{\nu_2+\nu_{2*}}R_3,\ R_3=k_3\rho\varphi_3 s_\sigma c_1\exp\left(-\frac{E_3}{RT_s}\right), h=h_3-h_1.$$

The system of equations (1)–(14) must be solved taking into account the initial and boundary conditions. At the initial time in the whole computational domain defined distribution of the unknown functions:

$$t=0: v_1=0,\ v_2=0, T=T_e, c_\alpha=c_{\alpha e}, T=T_e,\ \varphi_i=\varphi_{ie}\,. \tag{15}$$

Values of functions for the incoming flow in the left boundary are set as follows:

$$x_1=-x_{1e}: v_1=V_e, v_2=0, T=T_e, c_\alpha=c_{\alpha e}-\frac{c}{3k}\frac{\partial U_R}{\partial x_1}+cU_R/2=0. \tag{16}$$

On the right boundary set the following boundary conditions:

$$x_1 = x_{1e} : \frac{\partial v_1}{\partial x_1} = 0,\ \frac{\partial v_2}{\partial x_1} = 0, \frac{\partial T}{\partial x_1} = 0, \frac{\partial c_\alpha}{\partial x_1} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_1} + cU_R/2 = 0. \quad (17)$$

At the upper boundary of the computational domain boundary conditions will be as follows:

$$x_2 = x_{2e} : \frac{\partial v_1}{\partial x_2} = 0,\ \frac{\partial v_2}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_2} + cU_R/2 = 0. \quad (18)$$

Values of the functions in the hearth of ignition on the ground cover are set depending on the time:

$$\rho v_2 = h_0 \dot{m}, T = T_S = \begin{cases} T_e + t/t_0(T_0 - T_e), t \le t_0, \\ T_e + (T_0 - T_e)\exp\left[-k(t/t_0 - 1)\right], t > t_0 \end{cases} \quad (19)$$

At the interface forest canopy - the boundary layer of the atmosphere are given the following conditions:

$$\begin{aligned} &\rho v_2\big|_{x_2=h_-} = \rho v_2\big|_{x_2=h_+},\ -\rho\overline{v_1' v_2'}\big|_{x_2=h_-} = -\rho\overline{v_1' v_2'}\big|_{x_2=h_+}, \\ &v_1\big|_{x_2=h_-} = v_1\big|_{x_2=h_+},\ -\rho\overline{v_2'^2}\big|_{x_2=h_-} = -\rho\overline{v_2'^2}\big|_{x_2=h_+},\ v_2\big|_{x_2=h_-} = v_2\big|_{x_2=h_+}, \\ &-\rho\overline{v_2' c_\alpha'}\big|_{x_2=h_-} = -\rho\overline{v_2' c_\alpha'}\big|_{x_2=h_+},\ c_\alpha\big|_{x_2=h_-} = c_\alpha\big|_{x_2=h_+}, \\ &-\rho\overline{C_p v_2' T'}\big|_{x_2=h_-} = \rho\overline{C_p v_2' T'}\big|_{x_2=h_+},\ T\big|_{x_2=h_-} = T\big|_{x_2=h_+}, \\ &-\frac{c}{3k}\frac{\partial U_R}{\partial x_1}\big|_{x_2=h_-} = -\frac{c}{3k}\frac{\partial U_R}{\partial x_1}\big|_{x_2=h_+}. \end{aligned} \quad (20)$$

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,...,6, 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, 6 - dust particles containing radioactive pollution; 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. In equation (4) the total derivative components of the gas phase at α = 1-5 is as follows:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v_1\frac{\partial}{\partial x_1} + v_2\frac{\partial}{\partial x_2},$$

and for dispersed phase components at α = 6:

$\frac{d}{dt} = \frac{\partial}{\partial t} + v_1\frac{\partial}{\partial x_1} + (v_2 - v_{2\alpha}^{(s)})\frac{\partial}{\partial x_2}$, here $v_{2\alpha}^{(s)} = 18g\mu/\rho_\alpha^{(s)} d_\alpha^2$ - Stokes deposition rate of the dispersed particles, μ - molecular dynamic viscosity of the gas phase, g - acceleration of gravity, $\rho_\alpha^{(s)}, d_\alpha$ - the density and diameter of the dispersed particles [6,7].

Thus, in accordance with [1], the medium is considered a two-speed, to allow for sedimentation - deposition of particles under the influence of gravity. In the system (6) - (14) the values of τ, J_α, q_T characterize the exchange of momentum, mass and energy between the boundary layer of the atmosphere and the lower layers of the forest are determined by the appropriate boundary conditions. Thus, the set of equations (1) - (14) are the ratio of the mass balance, energy and momentum, which are setting conjugate problem, whose solution is to determine the characteristics of complex, interrelated propagation process of a forest fire. Solution the problem stated above is considerable mathematical difficulties. The values of τ, J_α, q_T generally be determined in the process of solving the conjugate problem.

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 [1].

$$R_1 = k_1\rho_1\varphi_1 \exp\left(-\frac{E_1}{RT_s}\right), R_2 = k_2\rho_2\varphi_2 T_s^{-0.5} \exp\left(-\frac{E_2}{RT_s}\right),$$

$$R_3 = k_3\rho\varphi_3 s_\sigma c_1 \exp\left(-\frac{E_3}{RT_s}\right), R_5 = k_5 M_2 \left(\frac{c_1 M}{M_1}\right)^{0.25} \frac{c_2 M}{M_2} T^{-2.25} \exp\left(-\frac{E_5}{RT}\right).$$

Thermodynamic, thermal and structural characteristics correspond FF pine forests [1] and is numerically equal to: E_1/R = 9400K, k_1 = 3.36·10^4 c^{-1}, q_1 =0, E_2/R = 6000K, k_2= 6·10^5 c^{-1}, q_2=3·10^6 J/kg, E_3/R=10^4 K, k_3=10^3 c^{-1}, q_3=1.2·10^7 J/kg, E_5/R=11500 K, k_5 =3·10^{13}, q_5 =10^7 J/kg, c_{p1}= 2000, c_{p2} = 4180, c_{p3} = 900, c_{p4} =1000, c_p = 1000 J/(kg ·K), s = 1000 m^{-1}, sc_d=0.1, α_C=0.06, $\rho_4\varphi_4$= 0.08 kg/m^3, ν=0.7, ρ_1 = 500, ρ_2= 1000, ρ_3= 200, ρ_e= 1.2 kg/m^3, c_{2e} = 0, φ_{3e} = 0, p_e = 10^5 N/m^2, T_e= 300 K, T_0= 1200 K, c_{1e} =0.23, c_{50} =0.09, α_4=0.66, α_6 =10^{-4}.

To close the system (1)–(14), the components of the tensor of turbulent stresses, and the turbulent heat and mass fluxes are determined using the local-equilibrium model of turbulence [1]. The system of equations (1)–(14) contains terms associated with turbulent diffusion, thermal conduction, and convection, and needs to be closed. The components of the tensor of turbulent stresses $\rho\overline{v_i' v_j'}$, as well as the turbulent fluxes of heat and mass $\rho\overline{v_j' c_p T'}$, $\rho\overline{v_j' c_\alpha'}$ are written in terms of the gradients of the average flow properties using the formulas:

$$-\rho\overline{v_i v_j} = \mu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_i}{\partial x_i}\right) - \frac{2}{3}K\delta_{ij},$$

$$-\rho\overline{v_j c_p T'} = \lambda_t \frac{\partial T}{\partial x_j},\ -\rho\overline{v_j c_\alpha'} = \rho D_t \frac{\partial c_\alpha}{\partial x_j},$$

$$\lambda_t = \mu_t c_p / \mathrm{Pr}_t, \rho D_t = \mu_t / Sc_t, \mu_t = c_\mu \rho K^2/\varepsilon,$$

where μ_t, λ_t, D_t are the coefficients of turbulent viscosity, thermal conductivity, and diffusion, respectively; Pr_t, Sc_t are the turbulent Prandtl and Schmidt numbers, which were assumed to be equal to 1. In dimensional form, the coefficient of dynamic turbulent viscosity is determined using local equilibrium model of turbulence [1]. For this case, assume that we can be neglected by non-stationary convective terms, as well as members of the diffusion of turbulent kinetic energy in the equation for the turbulent kinetic energy. Then the right-hand side of the equation, you can obtain an expression for the turbulent kinetic energy and, according to the coefficient of turbulent dynamic viscosity. To close the system of equations of the turbulent stress tensor components, turbulent flows, heat and mass are determined by the formulas. Use the local-equilibrium model of turbulence. To determine the turbulent dynamic viscosity in a two-dimensional case, we used the formula [1]:

$$\mu_t = \rho\left(\frac{c_\mu}{c_1}\right)^{3/2} l^2 \left\{2\left[\left(\frac{\partial v_1}{\partial x_1}\right)^2 + \left(\frac{\partial v_2}{\partial x_2}\right)^2\right] + \left(\frac{\partial v_2}{\partial x_1} + \frac{\partial v_1}{\partial x_2}\right)^2 - \frac{2}{3}\left(\frac{\partial v_2}{\partial x_1} + \frac{\partial v_1}{\partial x_2}\right) - \frac{g}{T\,\mathrm{Pr}_T}\frac{\partial \theta}{\partial x_2}\right\}^{1/2}, \quad (21)$$

where $\theta = T - T_e$, c_1, c_μ - constants. The length of the mixing path is determined using the formula $l = x_2 k_T /(1 + 2.5 x_2 \sqrt{c_d s/h})$ taking into account the fact that the coefficient of resistance c_d in the space between the ground cover and the forest canopy base is equal to zero, while the constants k_T = 0.4 and $h = h_2 - h_1$ (h_2, h_1 – height of the tree crowns and the height of the crown base). 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.

Calculation method and results

The boundary-value problem Eq. (1)–(14) we solve numerically using the method of splitting according to physical processes [13]. 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 [13] was then integrated. A discrete analog was obtained by means of the control volume method using the ***SIMPLE*** like algorithm [9]. The resulting systems of algebraic equations are solved by ***SIP*** method [6-9] for three dimensional cases. The accuracy of the program was checked by the method of inserted analytical solutions. Analytical expressions for the unknown functions were substituted in (1)–(14) and the closure of the equations was calculated. This was then treated as the source in each equation. Next, with the aid of the algorithm described above, the values of the functions used were inferred with an accuracy of not less than 1%. The effect of the dimensions of the control volumes on the solution was studied by diminishing them. The time interval was selected automatically.

Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically. Figures 2–5 *a*, b and c illustrate the distribution of relative temperatures, concentrations of radioactive products of combustion and velocity fields for different instants of time. Figures 2 a, b, c show the distribution of temperature, the concentration of the radioactive products and the combustion speed at the time of 220 seconds after the initiation of the crown fires. The wind speed was set equal to 7 m/s at a height of 14 meters above ground level. The level of contamination on the basis of the distributions of concentrations in radioactive products of combustion can be calculated, for example, per unit area according to the formula: $R = \gamma \int_0^{x_{2e}} c_6 dx_2$, where γ - quantity characterizing the level of radioactive contamination of the products of combustion per unit mass (eg, Ku/kg). Figures 2 *a*, b, c show that under the influence of the combustion source and wind velocity occur ascent of the radioactive hot combustion products and their transfer over long distances from the fire. Distribution corresponding functions after 10 minutes is shown in Figure 3. With increasing wind speed by 2 times, that is, to 14 m / c, and the concentration distribution of the isotherms pressed harder to the surface (Figure 4 *a*, b, As a result in this case combustion products more intensively move upward and in the vicinity of the fire front is a higher level of radioactive contamination in compare with previous situations.

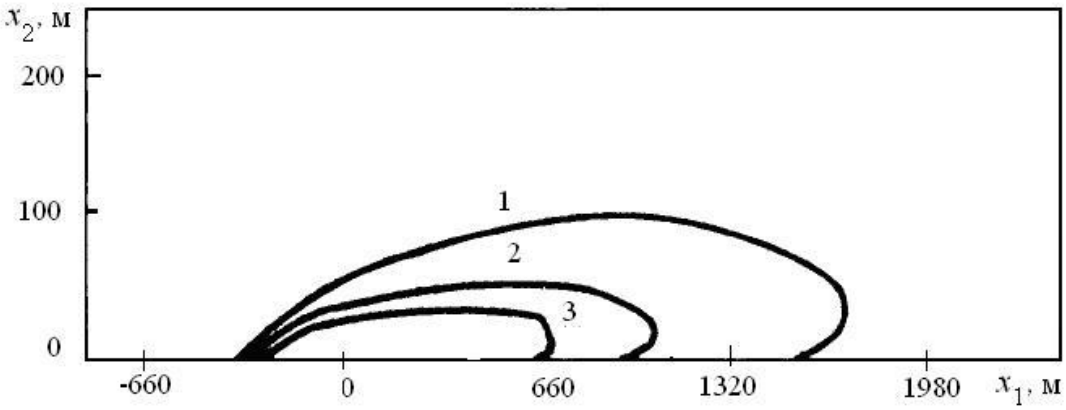

Figure. 2 *a*. $1-\overline{T}=1.01$; $2-1.05$; $3-1.1$; $\overline{T}=T/T_e$; $T_e=300\,K$.

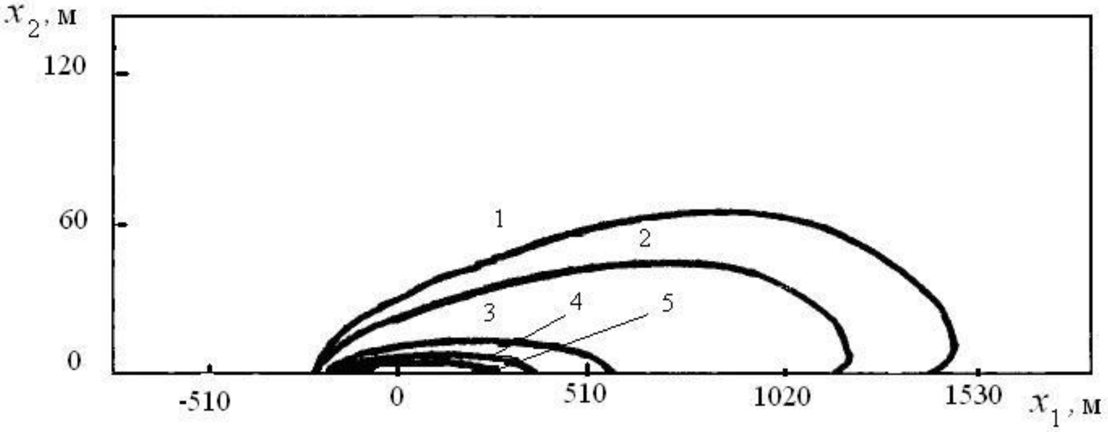

Figure 2 *b*. $1-C=0.005$ kg/m³; $2-0.01$ kg/m³; $3-0.05$ kg/m³; $4-0.1$ kg/m³; $5-0.15$ kg/m³.

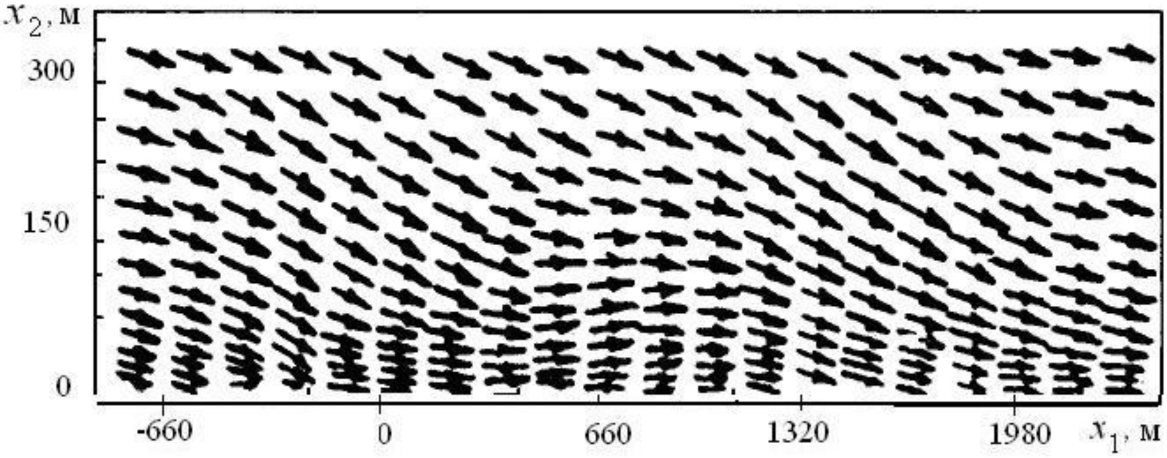

Figure 2 c. Vector flow field.

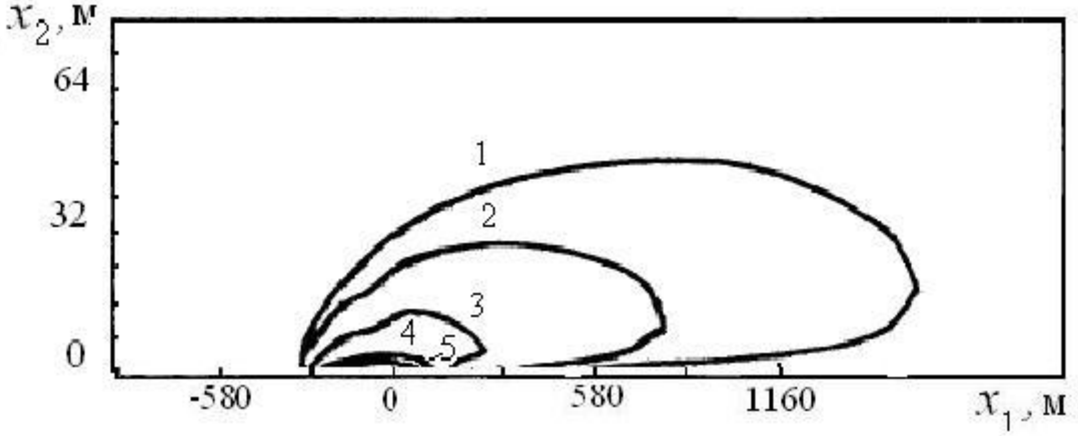

Figure 3 *a*. $1-\overline{T}=1.05;\ 2-1.1;\ 3-1.3;\ 4-2=2.5;\ 5-2.6.$

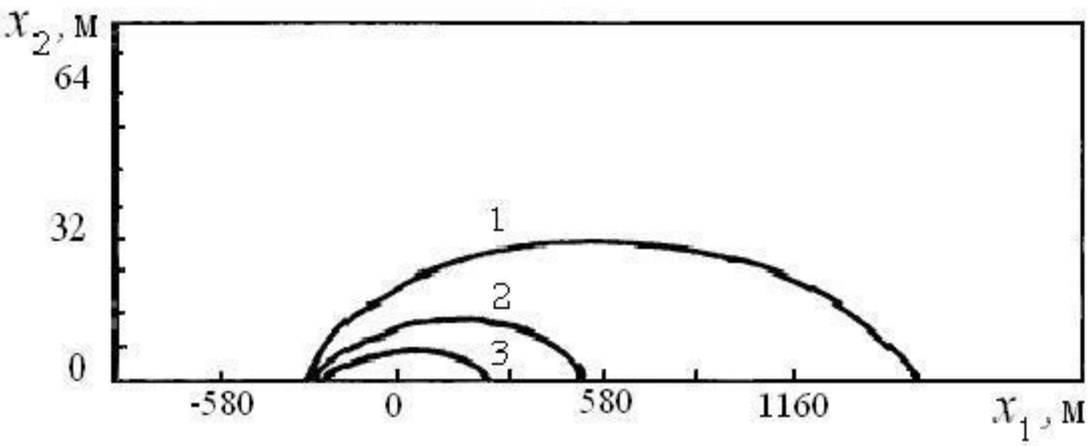

Figure 3 b. $1-C=0.02$ kg/m^3; $2-0.1$ kg/m^3; $3-0.3$ kg/m^3.

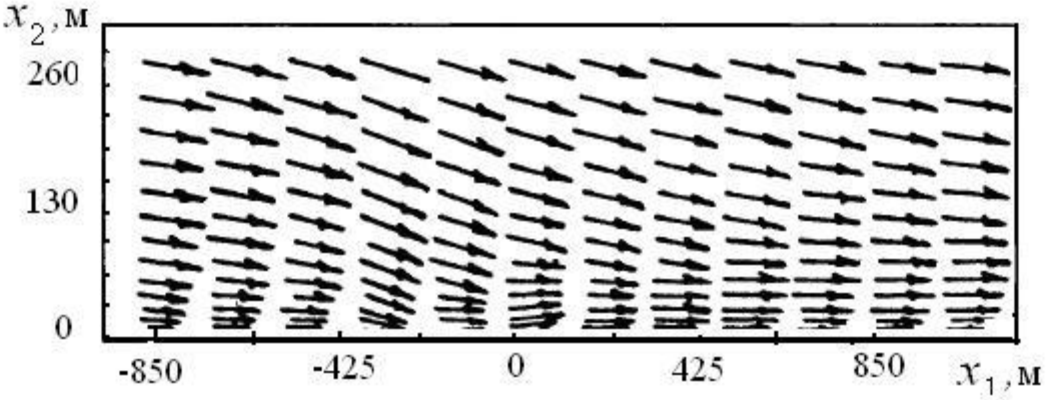

Figure 3 c. Vector flow field.

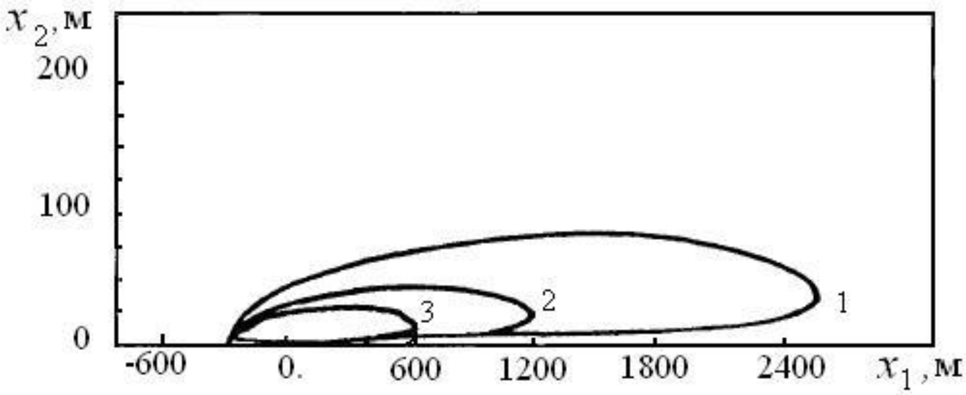

Figure 4 *a*. $1-\overline{T}=1.02;\ 2-1.05;\ 3-1.1$.

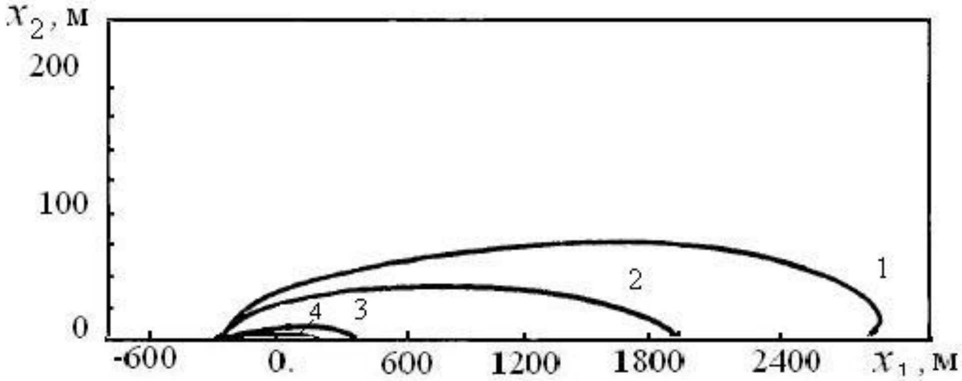

Figure 4 b. $1-C=0.005$ kg/m^3; $2-0.01$ kg/m^3; $3-0.05$ kg/m^3; $4-0.1$ kg/m^3.

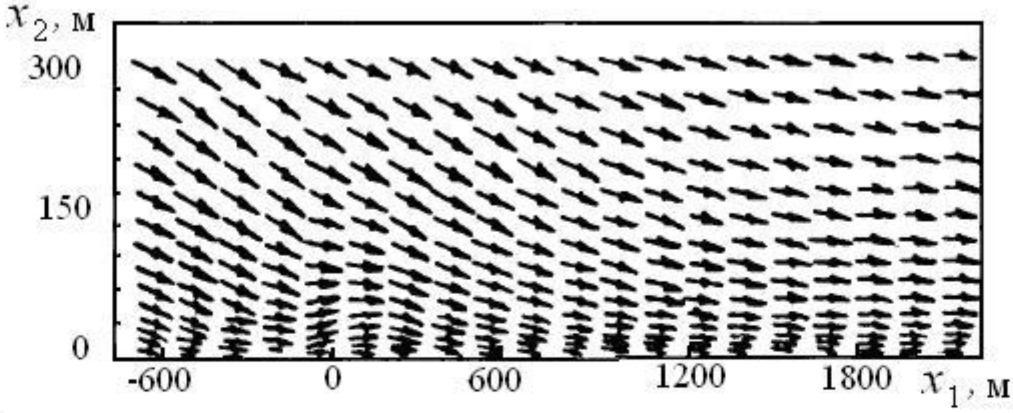

Figure 4.c. Vector flow field.

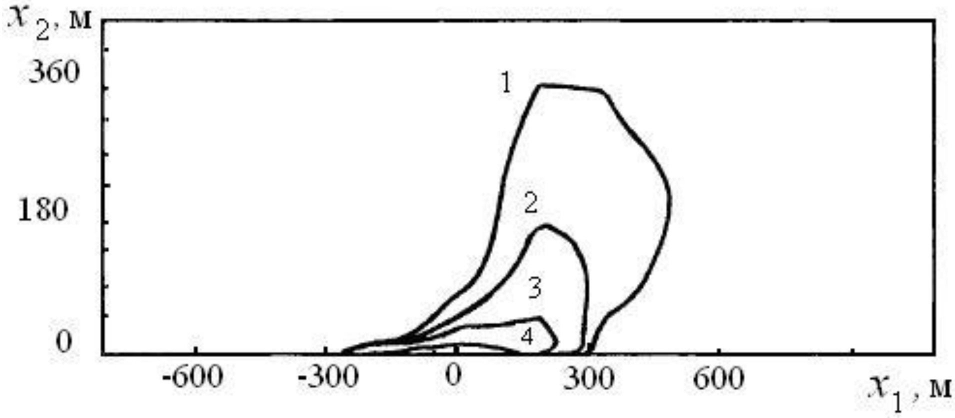

Figure 5 *a*. $1-\overline{T}=1.03;\ 2-1.05;\ 3-1.1; 4-2$.

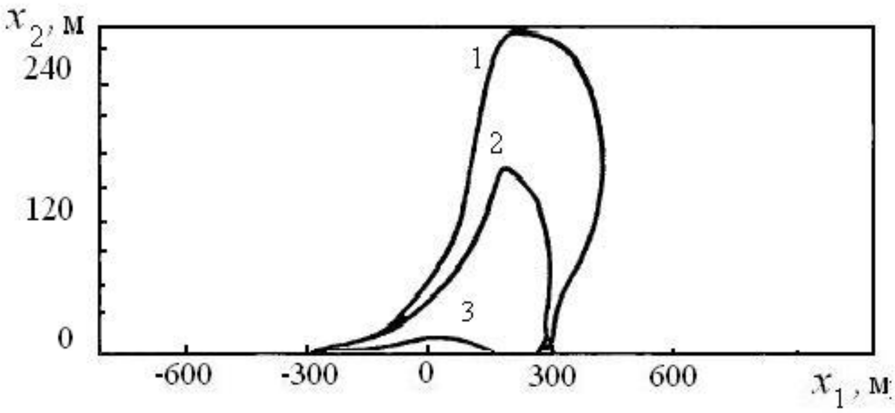

Figure 5 b. $1-C=0.007$ kg/m^3; $2-0.01$ kg/m^3; $3-0.05$ kg/m^3.

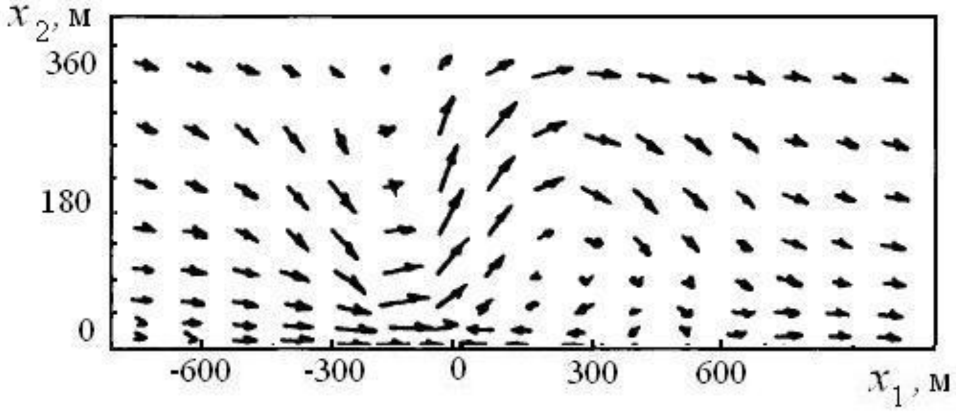

Figure 5 c. Vector flow field.

Thus, a mathematical model for prediction of the spread of radioactive contamination repeated forest fires in forests exposed to radioactive contamination as a result of accidents. In contrast to the mathematical model [6,7], where the calculated distribution of radionuclides in the vertical plane, and the front of a forest fire was set by means of boundary conditions, in this paper we consider the conjugate formulation of the problem. The system of equations to describe the crown forest fire and flow in the boundary layer of the atmosphere are solved separately, but takes into account their mutual influence with the help of (20). Obtained in this paper a mathematical model can be used in practice to determine the dynamics of the crown forest fire and to determine levels of re-contamination occurring during fires in forests exposed to radioactive contamination.

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