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Mathematical modeling of the initiation and spread of forest fires and their impact on buildings and structures

Currently, methods of mathematical modeling are used to study processes in emergency situations. Forest fires are extremely complex and destructive natural phenomena which depend on availability of fuel, meteorological and other conditions. Mathematical model of forest fire is based on an analysis of known experimental data and using concept and methods from reactive media mechanics. In this paper the theoretical study of the problems of crown forest fire spread in windy condition and their thermal impact on the wooden building were carried out. The research was based on numerical solution of two-dimensional Reynolds equations. The boundary-value problem is solved numerically using the method of splitting according to physical processes. A discrete analogue for the system of equations was obtained by means of the control volume method. A study of forest fire spreading made it possible to obtain a detailed picture of the change of the component concentration of gases and temperature fields in forest fire and on the wall of building with time. It let to determine the limiting distances between forest fire and building for possibility of wooden walls ignition for different meteorology conditions, size of building and intensity of fire impact.

Keywords: crown fire, fire spread, forest fire, mathematical model, ignition, finite volume method, building, turbulence.

Introduction

A number of authors are studying the problem of the behavior of forest fires. Rothermal [1] and Van Wagner [2] formulated the first mathematical methods to study the behavior of forest fires. They represent semi-empirical approaches that allow one to obtain fairly reliable values of the flame front propagation velocity, depending on a given supply and moisture content of forest combustible materials, wind speed and terrain. However, in their models, the authors used parameters for specific fires based on certain data. This limitation significantly reduces the possibility of widespread use of this method in modeling various forest fires. Numerical modeling based on identical installations is used to compare the effectiveness of two main approaches based on Eulerian LSM and Lagrangian DEVS schemes in constructing forest fire models [3]. The mathematical models presented in the works [4–9] provide more detailed conditions for the spread of forest fires. A distinctively new approach to studying the behavior of forest fires by the method of mathematical modeling was proposed by Grishin. [10], which is based on the application of experimental data and the use of approaches and methods of reactive mechanics [11]. However, when studying the problem of the behavior of forest fires [10, 11], the issue of the effect of the wildland fires front on buildings and structures located near the forest zone were not studied. In the summer season of 2019, according to official data, more than 2 million hectares of timber burned out as a result of forest fires in Russia. Such large-scale forest fires carry not only an economic threat, but also a threat to human victims as a result of the transition of the flame front to urban areas. Extinguishing forest fires requires a lot of effort and cost, creating airborne teams of firefighting specialists, engaging outside organizations and volunteer groups, etc., and, in the vast majority of cases, is ineffective or impossible. Currently, the most effective methods for studying natural fires are mathematical modeling methods using numerical methods [10–14] and modern software to solve problems.

Physical and mathematical setting

The mathematical model considered in this paper and the calculation results are used to study the interaction of forest fire fronts with wooden structures. We assume that on the ground cover there is an area of elevated temperature, that is, a center of a lower fire, which has some dimensions, at a certain height, above the forest canopy, the wind speed is set. Under the influence of this burning zone, inert heating of forest combustible materials takes place in the forest canopy, moisture evaporates, pyrolysis occurs with the release of condensed and volatile pyrolysis products, which then ignite. A combustion front is formed, which moves along the forest canopy under the influence of wind. If a building is located near the forest, then the flame front has a thermal effect on it due to the transfer of energy by radiation, convection and transfer of burning particles. As a result, ignition of this object is possible. Let us consider schematically the region of the process under consideration. The axis *0x*$_2$ is directed perpendicular to the earth surface, and the axis *0x*$_1$ is directed parallel to the earth surface and coincides with the direction of the wind. Figure 1 shows a scheme of this process:

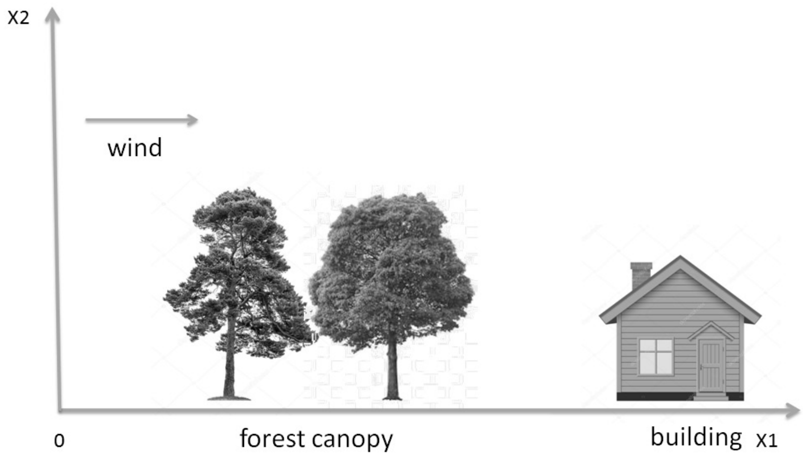


Figure 1. Forest fire propagation pattern

It is supposed that: 1) the flow is turbulence, while laminar transport is neglected, since it is not significant compared with turbulent; 2) the density of the gas-dispersed phase does not depend on pressure, due to the fact that the flow velocity is small relative to the speed of sound; 3) it is assumed that the local-thermodynamic equilibrium is taken place; 4) the wind speed is defined at height of the forest canopy; 5) the multiphase medium consist of particles of the condensed and gas phase (oxygen, gaseous combustible pyrolysis products and inert components (nitrogen, water vapor, gas products of combustion and etc.) [10, 12]. The problem given above reduces to solving the following system of differential equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = m, j = 1,2, i = 1,2; \quad (1)$$

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

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

$$\rho \frac{dc_\alpha}{dt} = \frac{\partial}{\partial x_j}(-\rho \overline{v_j' c_\alpha'}) + R_{5\alpha} - \dot{m} c_\alpha, \ \alpha = \overline{1,2}; \quad (4)$$

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

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

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

$$\sum_{\alpha=1}^{3} c_\alpha = 1, p_e = \rho RT \sum_{\alpha=1}^{3} \frac{c_\alpha}{M_\alpha}, \mathrm{v} = (\mathrm{v}_1, \mathrm{v}_2), g = (0, g); \qquad (8)$$

$$\dot{m} = (1-\alpha_c)R_1 + R_2 + \frac{M_c}{M_1}R_3, \ R_{51} = -R_3 - \frac{M_1}{2M_2}R_5, \ R_{52} = \nu(1-\alpha_c)R_1 - R_5, \ R_{53} = 0. \qquad (9)$$

This system of equations is solved using the next initial and boundary conditions:

$$t = 0: \mathrm{v}_i = 0, T = T_e, c_\alpha = c_{\alpha e}, T_s = T_e, \varphi_k = \varphi_{ke}, i = 1,2; k = 1,2; \alpha = 1,3; \qquad (10)$$

$$x_1 = -x_{1e}: \mathrm{v}_1 = V_e(x_2), \mathrm{v}_2 = 0, T = T_e, c_\alpha = c_{\alpha e}, -\frac{c}{3k}\frac{\partial U_R}{\partial x_1} + \frac{cU_R}{2} = 0; \qquad (11)$$

$$x_1 = x_{1e}: \frac{\partial \mathrm{v}_1}{\partial x_1} = 0, \frac{\partial \mathrm{v}_2}{\partial x_1} = 0, \frac{\partial T}{\partial x_1} = 0, \frac{\partial c_\alpha}{\partial x_1} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_1} + \frac{cU_R}{2} = 0; \qquad (12)$$

$$x_2 = 0: v_1 = 0, (\rho v_2) = h_0 m,$$

$$T = T_S = \begin{cases} T_e + (T_0 - T_e)\exp(-((x_1 - x_{10})/\Delta_x)^2)t/t_0, & t \le t_0 \\ T_e + (T_0 - T_e)\exp(-(((x_1 - x_{10}) - x_f)/\Delta_x)^2), & t > t_0 \end{cases},$$

$$-\rho D_t \frac{\partial c_\alpha}{\partial x_2} + \rho v_2 c_\alpha = h_0 R_{5\alpha}, \ -\frac{c}{3k}\frac{\partial U_R}{\partial x_3} = \frac{\varepsilon}{2(2-\varepsilon)}\left(4\sigma T_S^4 - cU_R\right); \qquad (13)$$

$$x_2 = x_{2e}: \frac{\partial \mathrm{v}_1}{\partial x_2} = 0, \frac{\partial \mathrm{v}_2}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2}U_R = 0, \qquad (14)$$

where x_1, x_2, v_1, v_2 — coordinates and corresponding projections of the velocity vector on the axes of coordinate; R_5 and $R_{5\alpha}$ — combustion reaction rates of gaseous pyrolysis products and the appearance of α — gas dispersed phase components; c_p ρ, — specific heat and density of the gas phase; T — the temperature of gas-dispersed phase; c_α — mass concentrations (α = 1 — oxygen, 2 — CO, 3 — inert air components); P — pressure; U_R — radiation energy density; σ — Stefan-Boltzmann constant; k_g — absorption coefficient for gas-dispersed phases; q_i, E_i, k_i — thermal effects of the reactions, activation energies, and pre-exponents of the reaction of pyrolysis, evaporation of moisture and combustion of pyrolysis products; M_α, M — molecular weights of the components of the gas phase and air mixture; c — speed of light; α_c, ν — coke number and mass fraction of combustible gases in the mass of gaseous pyrolysis products; g — gravitational constant. Indexes «*o*» и «*e*» relate to functions in the field of combustion and at a considerable distance from the fire front, respectively. Index «‘» used to indicate the pulsating components of various functions [10]. The thermodynamic, thermophysical, and structural quantities used in the statement of the problem belong to forest combustible materials corresponding to the pine forest: E_5/R = 11500 K, $k_5 = 3\cdot 10^{13}$, $q_5 = 10^7$ J/kg, c_p = 1000 J/(kg·K), α_c = 0.06, ν = 0.7, ρ_e = 1.2 kg/m^3, c_{2e} = 0, p_e = 10 N/m^2, T_e = 300 K, c_{1e} = 0.23 [12]. Turbulent stress tensor components $\rho\overline{v'w'}$ and turbulent heat and mass fluxes $\overline{v'T'}$, $\overline{v'c'_\alpha}$ computed using middle flow gradients as follows:

$$-\rho_5\overline{u_i u_j} = \mu_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial x_i}\right) - \frac{2}{3}K\delta_{ij}, ; -\rho_5\overline{u_j c_p T'} = \lambda_T\frac{\partial T}{\partial x_j}, \ -\rho_5\overline{u_j c'_\alpha} = \rho_5 D_T\frac{\partial c_\alpha}{\partial x_i}, \qquad (15)$$

$$\lambda_T = \mu_T c_p / \mathrm{Pr}_T, \rho_5 D_T = \mu_T / Sc_T, \mu_T = c_\mu \rho_5 K^2/\varepsilon, ; \ \mu_t = c_\mu \rho K^2/\varepsilon, \qquad (16)$$

where K — kinetic energy of turbulence, v_i and v_i' — components of the average velocity and the pulsating component of the velocity in the projection onto the axis x_i; μ_t, λ_t, D_t — coefficients of turbulent, dynamic viscosity, turbulent thermal conductivity and diffusion; Pr_t. Sc_t — turbulent Prandtl and Schmidt numbers; δ_{ij} — Kronecker characters; $\mu_t = c_\mu \rho K^2/\varepsilon$, where ε — dissipation rate of turbulent kinetic energy, c_μ — constant. The determination of the coefficient of turbulent dynamic viscosity has certain difficulties [10; 15], such as the arbitrariness in choosing the initial and boundary conditions for the kinetic energy equation of turbulence, as well as the approximate closure method, which is based on the Prandtl mixing path hypothesis, which actually means the equilibrium approximation for the kinetic energy equation turbulence. In [10], the approach for the two-dimensional planar case is described in more detail. If in the case under consideration the non-stationary and convective terms and the diffusion terms of turbulent kinetic energy are neglected in the equation for the kinetic energy of turbulence, then the coefficient of turbulent dynamic viscosity and the expression for the kinetic energy of turbulence can be obtained from the right side of the equation, as described in Grishin [10]. A locally equilibrium turbulence model is used. To determine the turbulent dynamic viscosity in the two-dimensional case, the next formula was used:

$$\mu_t = \rho l^2 \left\{ 2\left[\left(\frac{\partial v_1}{\partial x_1} \right)^2 + \left(\frac{\partial v_2}{\partial x_2} \right)^2 \right] + \left(\frac{\partial v_1}{\partial x_2} + \frac{\partial v_2}{\partial x_1} \right)^2 - \frac{2}{3}\left[\frac{\partial v_1}{\partial x_1} + \frac{\partial v_2}{\partial x_2} \right]^2 - \frac{g}{T\,\mathrm{Pr}_t} \frac{\partial \theta}{\partial x_2} \right\}^{1/2}, \tag{17}$$

where $\theta = T - T_e$. The formula for the mixing path proposed by the authors of [13] has the form

$$l = zk_T / (1 + 2.5z\sqrt{c_d s / h}), \tag{18}$$

where $k_t = 0.4$ — Karman constant, h — forest canopy height.

Numerical method

For numerical integration of the original system of equations, the control volume method is used [13]. The main meaning of this method is easily understood and lends itself to direct physical explanation. We divide the computational domain into a certain number of disjoint control volumes so that each node point is contained in only one volume. In the case of a two-dimensional problem, we consider a rectangle. The second step is the integration of the differential equation for each control volume. To carry out the calculation of the integrals, profiles are used that describe the change between the nodal points of the function Φ. The discrete analogue obtained as a result of integration expresses the conservation law for the state parameter Φ in each finite control volume [13]. The discrete analogue obtained in this way expresses the conservation law Φ for a finite control volume in the same way that the differential equation expresses the conservation law for an infinitely small control volume. An important property of this method is that the control volume method contains the exact integral conservation of such quantities as mass, momentum and energy for any group of control volumes and for the entire calculation area. This feature is demonstrated for any number of nodal points, and not only in the limiting case of a large number of them. Even a coarse grid solution satisfies precise integral balances [13]. Differential equations obeying the generalized conservation law describe the processes of hydrodynamics and heat transfer, mass transfer. When denoting any desired function of the variable Φ, the generalized differential equation takes the form in tensor form [13]:

$$\frac{\partial}{\partial t}(\rho\Phi) + \frac{\partial}{\partial x_i}(\rho v_i \Phi) = \frac{\partial}{\partial x_i}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_i} \right) + S_\Phi, \tag{19}$$

where, ρ is the density, t is the temporal coordinate, x_i is the spatial coordinate, v_i are the components of the velocity vector, Γ_Φ is the transport coefficient (Γ_Φ is the coefficient of thermal conductivity, turbulent viscosity, diffusion, etc.), S_Φ is the source term. In special cases, the heat flux as a result of chemical reactions in the energy equation or an increase (decrease) in component concentrations during chemical reactions in the diffusion equations may enter S_Φ. The specific form of Γ_Φ and S_Φ depends on the semantic load of the variable Φ. For the nodal point P the neighboring points W and E are located in the direction of the x_1 axis, points N and S (denoting north and south) — in the direction of the x_2 axis. The control volume surrounding point P is shown by lines. The volume depth in the z axis direction is assumed to be unity. Designations for distances Δx, $(\delta x)\ e$, etc., apply here to two dimensions. The question of the location of the faces of the control volume with respect to the nodal points remains open. You can position them exactly in the middle between adjacent points, but other methods can be applied, some of which will be discussed below. The discrete analog obtained here can be used in any such case.

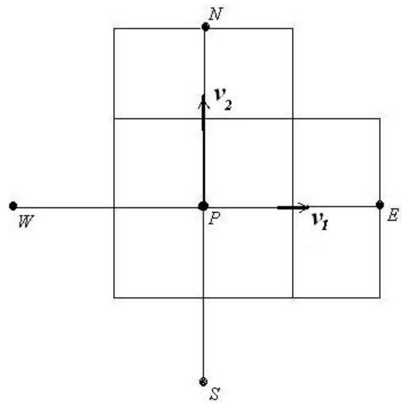


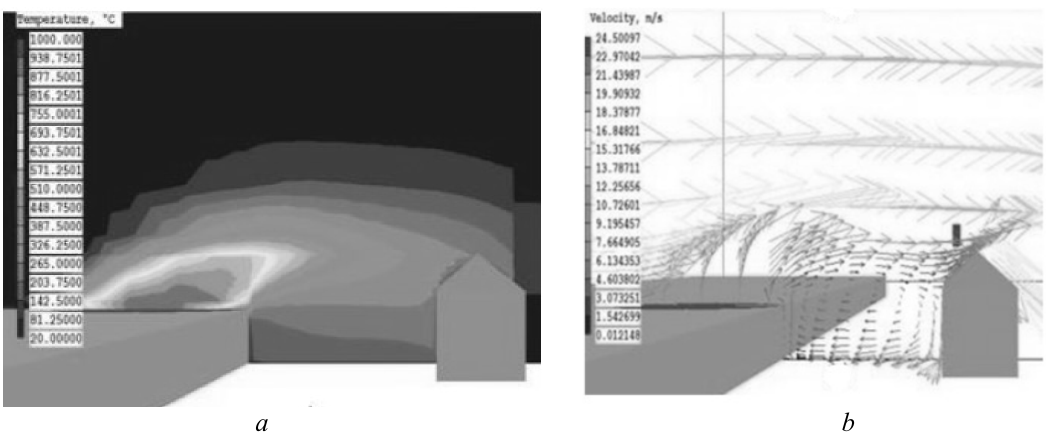
Figure 2. Control volume (shaded area) for the two-dimensional case

The calculated area is divided into a number of non-overlapping control volumes. Then we integrate the system of differential equations for each control volume [13]. As a result, we obtain a system of nonlinear algebraic equations, which is then solved numerically using the SIP method. Thus, we obtain the distributions of the sought-for functions at all points of the computational domain at different instants of time.

The results of calculations and their analysis

Using the described mathematical model, numerical calculations were carried out to determine the pattern of the ignition of a wooden structure as a result of the action of a flame front. The fields of the distribution of temperature, velocity, mass fractions of components, and volume fractions of phases were obtained numerically. The first stage is associated with an increase in the maximum temperature at the ignition site. As a result, a hotbed of flame appears. At this stage of the process, a heat flow arises above the hearth and a zone of heated wood pyrolysis products is formed, which mix with air, rise up and penetrate the tree crown. As a result, the forest canopy is heated in the crowns of trees, moisture evaporates and gaseous and dispersed pyrolysis products are formed. Ignition of gaseous pyrolysis products occurs in the next step. As a result of heating the wood, moisture evaporates, pyrolysis occurs, accompanied by the release of gaseous products, which then ignite and burn. At the time of ignition, gaseous combustible products are burned, and the oxygen concentration rapidly decreases. The temperatures of both phases reach their maximum value at the flash point. The calculation makes it possible to take into account the spread of forest fires at different wind speeds, bulk of forest fuel, and moisture of forest fuel. The influence of a forest fire on a building that is located near a forest is considered. The influence of wind speed and the distance between the forest and the building on the ignition of the building is studied numerically. The calculation results can be used to assess the thermal effect on a building located next to forest fires.

Fields of wind and temperature interact with an obstacle — construction (Fig. 3*a*) and *b*)). In Fig. 4 shows the results of modeling the wall temperature at different distances between the front of a forest fire and a wooden building (20×50×20 meters) for various values of wind speed from 3 to 15 m/s.



a *b*

Figure 3. Distribution of temperature *a*) and speed *b*) near the building

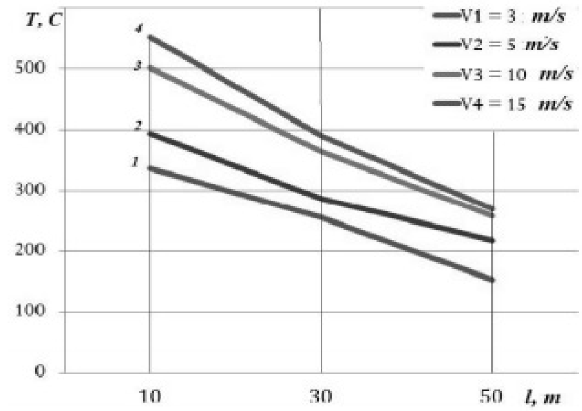


Figure 4. The temperature distribution on the wall of a wooden structure (20×50×20)
for different wind speeds (3–15 m/s) and for different distances *l* (10–50 m)

An analysis of this relationship shows the following: 1) a wooden structure with a wind speed of 3 m/s lights up at a distance of 15–16 meters from forest fires; 2) with $v = 5$ m/s — $l \approx 26$–27 meters; 3) $v = 10$ m/s — $l \approx 39$–40 meters; 4) $v = 15$ m/s — $l \approx 46$–47 meters. In Figure 5 shows the temperature dependence on the walls of a wooden house measuring 12×15×12 meters for different wind speeds (3–15 m/s) for distances *l* (10–50 m).

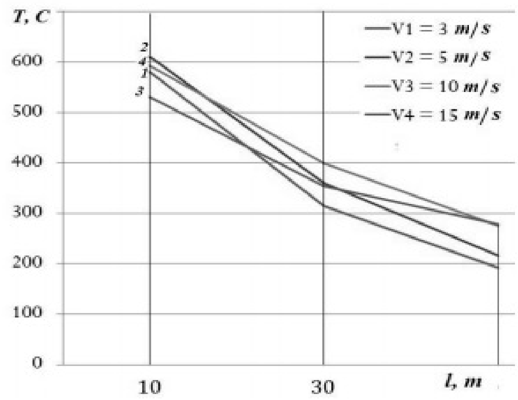


Figure 5. The temperature distribution on the wall of a wooden structure (12×15×12 m)
for different wind speeds (3–15 m/s) and for different distances *l* (10–50 m)

An analysis of this relationship (Fig. 5) shows the following: 1) a wooden structure with a wind speed of 3 m/s lights up at a distance of 32–33 meters from forest fires; 2) $v = 5$ m/s — $l \approx 38$–39 meters from forest fires; 3) $v = 10$ m/s — $l \approx 43$–44 meters from forest fires; 4) $v = 15$ m/s — $l \approx 42$–43 meters.

Conclusion

The result of solving this problem allows you to get a detailed picture of the change in speed, temperature and concentration fields of components in the wildland fire and on the near located buildings over time. This allows to study the dynamics of the impact of forest fires on wooden buildings under the influence of various external conditions, such as, meteorological conditions (air temperature, wind speed, etc.) and the type of forest combustible material and its state (bulk of forest fuel, moisture, etc.). Calculations make it possible to obtain the maximum safe distance from the forest fire front to the structures (buildings and other objects) in order to exclude the possibility of its ignition.

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В.А. Перминов, К.О. Фрянова

Орман өрттерінің пайда болуы мен таралуын және олардың ғимараттар мен құрылыстарға әсерін математикалық модельдеу

Қазіргі таңда төтенше жағдайлардың қозғалыстарын зерттеу үшін математикалық модельдеу әдістері қолданылады. Орманнан шығатын өрттер өте қауіпті өрттер болып саналады, олар отынның метеорологиялық және басқа жағдайлардың болуына байланысты пайда болады. Орман өртінің математикалық моделі белгілі эксперименттік мәліметтерді талдауға және реакциялық ортаның механикалық түсінігі мен әдістерін қолдануға негізделген. Зерттеу барысы желдің әсерінен орман өрттерінің таралуы мен олардың ағаш құрылымына термиялық әсері туралы теория жүзінде берілген. Зерттеу екі өлшемді Рейнольдс теңдеулерінің сандық шешіміне негізделген. Шеттік есеп физикалық қозғалыстарға бөлу әдісімен сандық түрде шешіледі. Теңдеулер жүйесіне арналған дискретті аналогы басқару көлемінің әдісі арқылы алынды. Орман өрттерінің таралуын зерттеу — орман өртінің алдындағы ғимарат қабырғасында газ тәрізді құрамдас бөліктердің және температура өрістерінің концентрациясының өзгеруінің нақты көрінісін алуға мүмкіндік береді. Бұл бізге әртүрлі метеорологиялық жағдайларда ағаш қабырғалардың тұтану мүмкіндігін, ғимараттың көлемі мен өрттің қарқындылығы үшін орман өрті мен ғимарат арасындағы ең үлкен қашықтықты анықтауға мүмкіндік береді.

Кілт сөздер: өрттің таралуы, орманның жануы, орман өрті, математикалық модель, тұтану, шектеулі көлем әдісі, құрылыс, турбуленттілік.

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Математическое моделирование возникновения и распространения лесных пожаров и их воздействие на здания и сооружения

В настоящее время методы математического моделирования используются для изучения процессов в чрезвычайных ситуациях. Лесные пожары являются чрезвычайно сложными и разрушительными природными явлениями, которые зависят от наличия топлива, метеорологических и других условий. Математическая модель лесного пожара основана на анализе известных экспериментальных данных и использовании концепции и методов механики реагирующих сред. В статье теоретически исследованы проблемы распространения лесных пожаров под действием ветра и их термическое воздействие на деревянное строение. Исследование было основано на численном решении двумерных уравнений Рейнольдса. Краевая задача решена методом расщепления по физическим процессам. Дискретный аналог для системы уравнений был получен методом контрольного объема. Изучение распространения лесных пожаров позволило получить детальную картину изменения концентрации газообразных компонентов и температурных полей во фронте лесного пожара и на стене здания в различные моменты времени. Это позволило определить предельные расстояния между лесным пожаром и зданием для возможности возгорания деревянных стен при различных метеорологических условиях, размерах здания и интенсивности воздействия огня.

Ключевые слова: верховой пожар, распространение пожара, лесной пожар, математическая модель, зажигание, метод конечных объемов, здание, турбулентность.

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