Теоретические основы информатики

Theoretical foundations of computer science

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ИНСТРУМЕНТАРИЙ АНАЛИЗА И ВИЗУАЛИЗАЦИИ РАСПРЕДЕЛЕНИЙ И ВЕКТОРНЫХ ПОЛЕЙ ПРИ МОДЕЛИРОВАНИИ НИЗОВЫХ ЛЕСНЫХ ПОЖАРОВ

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Рассмотрена задача компьютерного моделирования распространения низовых лесных пожаров в двумерной постановке. Приведена формулировка начально-краевой задачи в виде системы дифференциальных уравнений с частными производными в принятом приближении соответствующих физико-химических процессов с уточнениями взаимосогласованных определяющих функций и коэффициентов, включаемых в уравнения. Для разработки компьютерной модели, проведения расчетов и формирования базы данных с результатами вычислений использована система компьютерной алгебры *Wolfram Mathematica*. Представлены данные вычислительных экспериментов по изучению возможных сценариев распространения зоны горения вблизи противопожарных разрывов в тылу, на флангах

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и фронте пожара. С помощью многомерной графики проиллюстрированы несколько качественных особенностей структуры температурного фронта и его эволюции, векторных полей градиента концентрации кислорода по площади лесного массива при наличии имеющих различные формы и размеры участков с низким содержанием горючего материала и продемонстрировано влияние равновесной скорости ветра в пологе леса. На примерах показаны возможные варианты динамики фронта пожара в направлениях по ветру и против него.

Ключевые слова: низовой лесной пожар; математическая модель; программный комплекс; динамика фронта пожара; градиент концентрации кислорода; неоднородность напочвенного покрова; скорость ветра.

TOOLS FOR THE ANALYSIS AND VISUALISATION OF DISTRIBUTIONS AND VECTOR FIELDS IN SURFACE FOREST FIRES MODELLING

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The problem of computer modelling of the spread of surface forest fires in a two-dimensional formulation is herein considered. We describe the initial-boundary value problem in the form of a system of partial differential equations in the accepted approximation of the corresponding physical and chemical processes with refinements of the mutually agreed defining functions and the coefficients included in the equations. The *Wolfram Mathematica* computer algebra system is used as a platform for developing the computer model, performing calculations, and creating a database with the outcomes of computations. The results of numerical experiments investigating possible scenarios of how a fire zone spreads in different directions and its behaviour near the fuelbreaks are presented. Several qualitative features of the structure, the evolution of the temperature front, and the vector fields of the oxygen concentration gradient over the forest area are identified and illustrated with multidimensional graphics in the presence of areas of the low content of combustible materials of various shapes and sizes, including the demonstration of the influence of the equilibrium wind speed in the forest canopy. Possible variants of the fire front movement in the direction of the wind velocity and against it are identified and explained using representative examples.

Keywords: surface forest fire; mathematical model; software; fire front dynamics; oxygen concentration gradient; distribution of forest fuel; wind speed; wildfire.

Introduction

The influence of forest fires on the ecology and the environment, in particular, on air pollution, is well known. It manifests itself on a global scale, and has negative social and economic consequences [1–4]. In the territories of many regions, emergency situations caused by forest fires occur at regular intervals, and at the same time, the success in their prevention and extinguishing does not increase. Therefore, it is important to search for new solutions, technologies to prevent and reduce the intensity and duration of fires. The development of mathematical, computer models of forest fires began in the middle of the last century in the United States and continues throughout the world nowadays. A review of scientific publications indicates both successes and unresolved issues [5–9]. In particular, there is no convincing proof for the kinetics of physicochemical transformations and reactions used in the models [10; 11]. There are different, sometimes contradictory, models of turbulence processes in the gas phase [12; 13]. The available field experiments do not fully meet the real conditions; therefore, they cannot be considered representative. Until now, no balance has been found between mathematical models. Some models use too many simplifications, which lead to results that do not correspond to reality; other models, on the contrary, take into account many theoretically justified descriptions, for the verification of which there is insufficient experimental field data.

In most of the computer models given in the literature, the process of forest fire propagation is described and analysed only for homogeneous environments. However, in reality, a homogeneous distribution of forest fuel (mosses, litter, grasses, shrubs, trees, etc.) is extremely rare [5]. It is known that some observed effects of forest fires are caused precisely by heterogeneity. For example, the accelerated spread of fire along clearings, or the formation of a fire front in the form of «fingers» (fire fingering pattern [14]).

According to the existing reviews [15–19], mathematical (computer) models of forest fires are usually classified as physical, semi-empirical (including statistical), and simulation. In the presented research, the theoretical model of professor A. M. Grishin [20] is used. It is considered to be the most complete mathematical description of the spread of fires in forests and peat bogs. After the publication of the mentioned monograph, many researchers [9; 21–23], including the authors of this work, use Grishin's descriptions as a basis and modify them [24] for practical use [25], ensuring that the specific conditions of the territories and climate are taken into account.

Until recently [26; 27], the mathematical model of surface forest fires was used by the authors mostly in a one-dimensional formulation. This paper presents the results of modelling in a two-dimensional formulation, when spatially distributed processes are analysed in numerical experiments. Calculations of possible scenarios of forest fires spread are outlined, discussed, and illustrated; interrelated features in distributions of temperature and of oxygen concentration gradients caused by inhomogeneities in the density of combustible vegetation on the area are identified, interpreted, and visualised; the influence of wind direction and velocity is also taken into account.

In order not to refer readers to previous publications, we provide and explain the main formulas of the model and additions to them.

The mathematical model of forest fires spread

To obtain the results of this study, the problem is considered in a two-dimensional approximation (averaging over the height of forest fuel). The adopted mathematical model of forest fire spread takes into account the main processes of energy and mass transfer: heat supply caused by convection, thermal conductivity, and radiation; evaporation of water from forest fuel due to heating; decomposition of the dry organic matter of forest fuel into components, combustion of gaseous and afterburning of solid pyrolysis products [24–29]. The corresponding mathematical description implies the need to calculate the area distributions and the dynamics of the following values: T is the temperature of the continuous multiphase reacting medium measured in Kelvins; φ_j ($j = 1, 2, 3, 4$) are volume fractions of the components of the forest fuel material, where φ_1 denotes the dry organic matter of forest fuel, φ_2 is water contained in vegetation in bound and free forms, φ_3 is the condensed pyrolysis product, φ_4 is the non-combustible mineral part (ash) of forest fuel; c_ν ($\nu = 1, 2, 3$) are the relative mass concentrations of the components of a gaseous phase, where c_1 corresponds to oxygen, c_2 corresponds to the combustible gases arising in the process of thermal decomposition, c_3 is used for a mixture of other non-combustible gases, including water vapour resulting from drying, the carbon dioxide released during the afterburning of coke and the oxidation of combustible gases, inert components of the air mixture, and the products of pyrolysis and combustion reactions.

The functions T, φ_1, φ_2, φ_3, φ_4, c_1, c_2, c_3 depend on both time t and spatial coordinates x and y. The surface forest fire model is formulated as an initial-boundary value problem in the form of a system of partial differential equations (1)–(11):

$$\frac{\partial \varphi_1}{\partial t} = \Phi_{\varphi_1}, \ \frac{\partial \varphi_2}{\partial t} = \Phi_{\varphi_2}, \ \frac{\partial \varphi_3}{\partial t} = \Phi_{\varphi_3}, \ \frac{\partial \varphi_4}{\partial t} = 0, \tag{1}$$

$$\frac{\partial c_1}{\partial t} + \left(V, \ \mathrm{grad} c_1\right) - \frac{1}{\rho_5}\mathrm{div}\left(\rho_5 D_T \mathrm{grad} c_1\right) = \Phi_{c_1}, \tag{2}$$

$$\frac{\partial c_2}{\partial t} + \left(V, \ \mathrm{grad} c_2\right) - \frac{1}{\rho_5}\mathrm{div}\left(\rho_5 D_T \mathrm{grad} c_2\right) = \Phi_{c_2}, \tag{3}$$

$$\frac{\partial T}{\partial t} + \frac{\rho_5 c_{p_5}\left(V, \ \mathrm{grad} T\right) - \mathrm{div}\left(\lambda_T \mathrm{grad} T\right)}{\rho_5 c_{p_5} + \sum\limits_{j=1}^{4} \rho_j \varphi_j c_{p_j}} = \Phi_T. \tag{4}$$

Let us note that the right-hand sides of differential equations (1)–(4) represent functions depending on the calculated variables. In particular, Φ_{φ_1} depends on φ_1 and T, the function Φ_{φ_2} depends on φ_2 and T, and Φ_{φ_3} depends on φ_1, φ_3, c_1, c_2, and T. These functions are expressed by the following formulas:

$$\Phi_{\varphi_1} = -\frac{R_1}{\rho_1}, \ \Phi_{\varphi_2} = -\frac{R_2}{\rho_2}, \ \Phi_{\varphi_3} = \frac{\alpha_c R_1}{\rho_3} - \frac{M_C}{M_1}\frac{R_3}{\rho_3}, \tag{5}$$

$$\Phi_{c_1} = \frac{1}{\rho_5}\left(R_{51} - c_1 Q - \frac{\alpha}{c_{p_5}\Delta h}\left(c_1 - c_{1\infty}\right)\right), \tag{6}$$

$$\Phi_{c_2} = \frac{1}{\rho_5}\left(R_{52} - c_2 Q - \frac{\alpha}{c_{p_5}\Delta h}\left(c_2 - c_{2\infty}\right)\right), \tag{7}$$

$$\Phi_T = \frac{-q_2 R_2 + q_3 R_3 + q_5 R_5 - \dfrac{\alpha}{\Delta h}\left(T - T_\infty\right) - 4\kappa_R \sigma T^4}{\rho_5 c_{p_5} + \sum\limits_{j=1}^{4} \rho_j \varphi_j c_{p_j}}, \tag{8}$$

$$\sum_{\nu=1}^{3} c_\nu = 1,\ \rho_5 = \frac{\rho_\infty T_\infty}{M_\infty T}\left(\sum_{\nu=1}^{3}\frac{c_\nu}{M_\nu}\right)^{-1},\ Q = \left(1 - \alpha_c\right) R_1 + R_2 + \frac{M_C}{M_1} R_3, \tag{9}$$

$$R_1 = k_{01}\rho_1\varphi_1 \exp\left(-\frac{E_1}{RT}\right),\ R_2 = k_{02} T^{-1/2}\rho_2\varphi_2 \exp\left(-\frac{E_2}{RT}\right),\ R_3 = k_{03} s_\sigma \varphi_3 \rho_5 c_1 \exp\left(-\frac{E_3}{RT}\right), \tag{10}$$

$$R_{51} = -R_3 - \frac{R_5 M_1}{2M_2},\ R_{52} = \left(1 - \alpha_c\right)\nu_\Gamma R_1 - R_5,\ R_5 = \rho_5 \min\left(c_2, \frac{M_2}{2M_1} c_2\right) k_{CO} \exp\left(-\frac{E_{CO}}{RT}\right). \tag{11}$$

Here t is time; T_∞ corresponds to the unperturbed ambient temperature; V is an equilibrium wind speed; Δh is the height of the forest fuel layer; ρ_j (j = 1, 2, 3, 4) is the true (particle) density of the φ_j component; ρ_5 is the density of a gas phase (a mix of gases); ρ_∞ is the unperturbed density of a mix of gases (air density); λ_T and D_T are the turbulent thermal conductivity and the diffusion coefficient [20]; α is the heat exchange between the atmosphere and the forest fuel layer; κ_R is the integral (absorption and scattering) attenuation coefficient; σ is the Stefan – Boltzmann constant; q_2, q_3, and q_5 are the heat effects of evaporation, of charcoal burning, and of gaseous combustible pyrolysis products burning; k_{01}, k_{02}, k_{03} and E_1, E_2, E_3 are the pre-exponential (frequency) factors and energy activations of reactions R_1, R_2, R_3. The universal gas constant is denoted by the symbol R; $c_{1\infty}$ and $c_{2\infty}$ are the relative mass concentrations in the unperturbed atmosphere of oxygen and of combustible gases; M_1, M_2, M_3, and M_C are the molecular masses of the gas phase components and of the condensed pyrolysis product; M_∞ is the molecular mass of air; c_{p_j} (j = 1, 2, 3, 4) are specific heat capacities of the φ_j component; c_{p_5} is the specific heat capacity of a gas phase. Here R_1, R_2, R_3 correspond to reactions of dry forest fuel pyrolysis (chemical decomposition of a substance by heating with an allocation of combustible gases), moisture evaporation from the forest fuel (drying), and condensed pyrolysis products burning; R_{51}, R_{52}, R_5 are the mass rates of oxygen disappearance, combustible gases generation, and combustible gases burning accordingly.

The mathematical model is focused on solving a very wide range of problems, on the possibility of reproducing many qualitative features. Below we discuss the results of calculations when specific values and expressions of coefficients and functions are used to characterise the composition and geometry of the distribution of the forest fuel, the rates of drying, pyrolysis, combustion, and others. The appropriate selection of values for the model supply was made so that there were no contradictions with the reasoned data given in the literature, in particular, with experimental studies [20; 23].

Let us list the values of the coefficients and the determining parameters of the model used in this work. They are selected based on the results of computational experiments in such a way as to demonstrate the features of forest fire processes: the starting temperature of the environment T_∞ = 304 K, the parameters of the layer of combustible vegetation (height Δh = 0.1 m, bulk density ρ_0 = 5 kg/m^3, moisture content W = 10 %, coke number α_c = 0.1); the turbulent processes in the gas phase (D_T = 1.5 m^2/s, λ_T = 1000 J/(m · s · K)); the energy and mass transfer coefficients (κ_R = 1.5 m^{-1}, α = 100 W/(m^2 · K)). The values for the densities of the forest fuel components, molecular masses, heat capacities, coefficients of physicochemical reactions, and several other values are given in [26].

The initial and boundary conditions are given in [25–29].

Software for calculating the forest fire dynamics

Approximate solutions of the reduced system of differential equations are calculated using explicit finite-difference schemes. The spatial grid is locally uniform and adapted in real-time by taking into account the resulting distributions. The time step is determined by the stability conditions [28; 29], taking into account the peculiarities and intensity of physicochemical processes at each time layer [30]. The current calculation results at the specified time points of the process are recorded in the database and separately visualised during processing and analysis. The creation of such a database of numerical experiments allows for the intelligent processing of the results. Computer algebra system *Wolfram Mathematica* is used as the basis of a software platform [31; 32].

The results presented below were preceded by methodological calculations, in which the steps of the spatial grid were selected based on the Runge rule. Special attention was paid to the issues of adequate correct visualisation, in particular, when constructing density maps and vector fields.

Below, we present and discuss the results of calculations of how the distributions of the main characteristics of fire are changed over time in a quadratic forest area with a side of 20 m. The process of fire development is studied in a forest when a fire occurs in the centre of the region (taken as the origin of coordinates) and the combustion begins to spread. It is considered that the wind in the forest canopy is directed along the *Ox* axis (from left to right). At the same time, on one of the flanks, there are areas with the absence of combustible vegetation (glades) [33].

The fig. 1–11 below show the volume density of the forest fuel; the green colour shows areas where the forest is in its initial state, the brown colour shows areas with no combustible material (fuelbreaks), the already burned forest areas are shown in dark blue. Also, the position and shape of the temperature of the current combustion front are synthesised in the same figures using gradient colours (from blue through white and yellow to red) as a distribution density map. The «drops» markers show the directions of the gradients of the oxygen mass concentration; the size of the «drops» is scaled by intensity.

Fire front propagation through fuelbreaks of various sizes

The examples below consider the options for the development of fires on areas of a forest with the uniform density of the forest fuel with inclusions in which there is no forest combustible material – round glades of various sizes (schematically shown in fig. 1). Small glades have an area of 2.25 m^2, the medium size is 4.5 m^2 (twice as large), and the large is 18 m^2, i. e., four times the area of the middle glade.

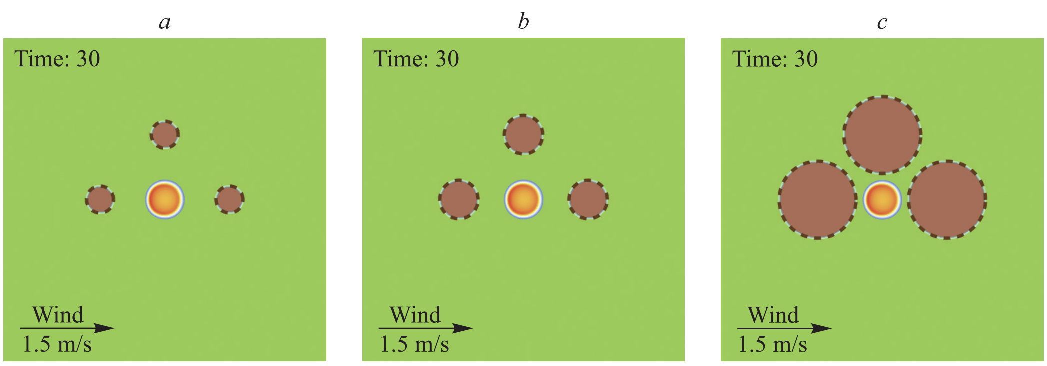

Fig. 1. Circular fuelbreaks of various sizes: 2.25 m^2 (*a*), 4.5 m^2 (*b*) and 18 m^2 (*c*) respectively (time point is 30)

Figures 2–4 show the results of calculations at an equilibrium wind speed at the middle of the flame height V = 1.5 m/s for three different sizes of fuelbreaks. The geometry differs only in the area of the clearings. The contour of the boundaries of the fuelbreaks and the positions of their centres relative to the combustion centre are the same for all three options. The distributions are rendered at the same points in time.

The illustrations can be interpreted as follows. During the first stage, the line of the fire contour breaks after meeting the glades. In the second stage, the fire «goes around» the glades. The fire propagation stops in the direction opposite to the direction of the wind. In the direction of the wind and across (perpendicular) to the direction of the wind, independent flanks meet together and the fire continues to spread as a united front. There is an evident difference in the front configurations after overcoming fields of different sizes [27].

In fig. 2–4 «drops» illustrate the directions and magnitude of the oxygen concentration gradient. The markers are shown only in the fire zone; in the areas not affected by the fire, the values of the simulated gas concentrations and temperatures are constant, the gradient is zero.

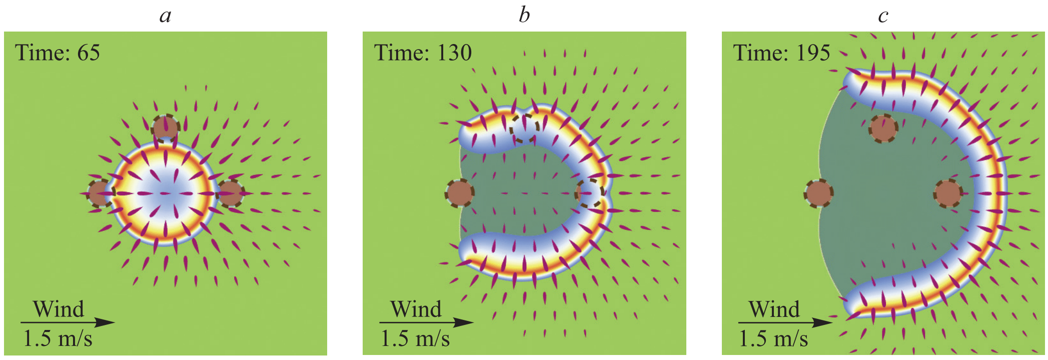

Fig. 2. Fire spread in the case of three fuelbreaks
with 2.25 m^2 each at the following time points: 65 (*a*), 130 (*b*), 195 (*c*)

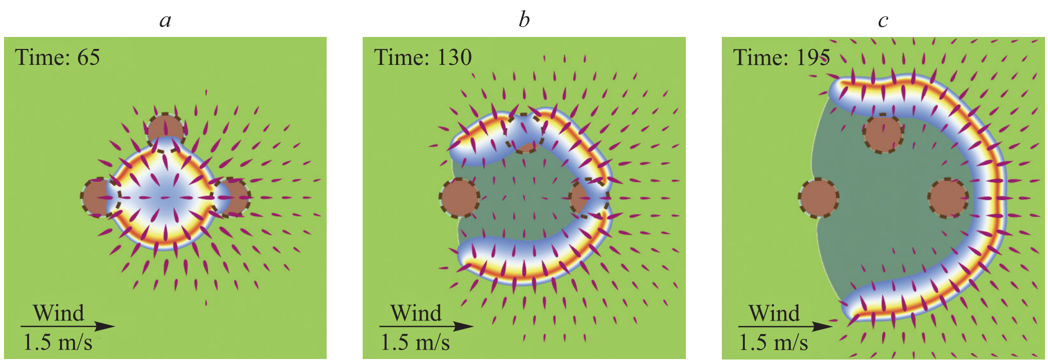

Fig. 3. Fire spread in the case of three fuelbreaks
with 4.5 m^2 each at the following time points: 65 (*a*), 130 (*b*), 195 (*c*)

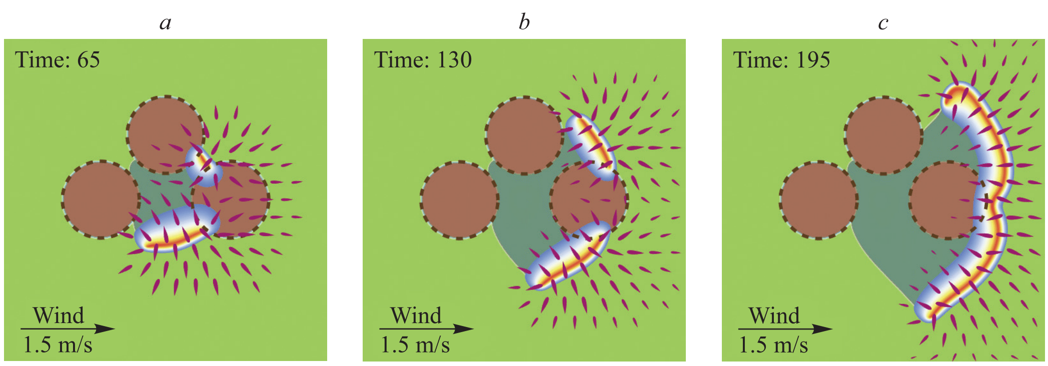

Fig. 4. Fire spread in the case of three fuelbreaks
with 18 m^2 each at the following time points: 65 (*a*), 130 (*b*), 195 (*c*)

Let us point out a general pattern. Because combustion (increase in temperature) is a process inextricably linked with a decrease in the oxygen concentration, then near the combustion fronts [6], the oxygen concentration gradients are collinear with the directions of movement of the edges of the fire.

Modelling the influence of fuelbreak forms on forest fire processes

The next series of computational experiments are intended to demonstrate the difference in the behaviour of a forest fire depending on the shape (see fig. 5) of the glades encountered in the path of the fire: rectangles (see fig. 6), squares (see fig. 7), and circles (see fig. 8). Please note that the difference is in the shapes of fuelbreaks, but the areas are the same. The time points shown in the illustrations also coincide. The calculations were carried out at an equilibrium wind speed at the middle of the flame height $V = 1.5$ m/s.

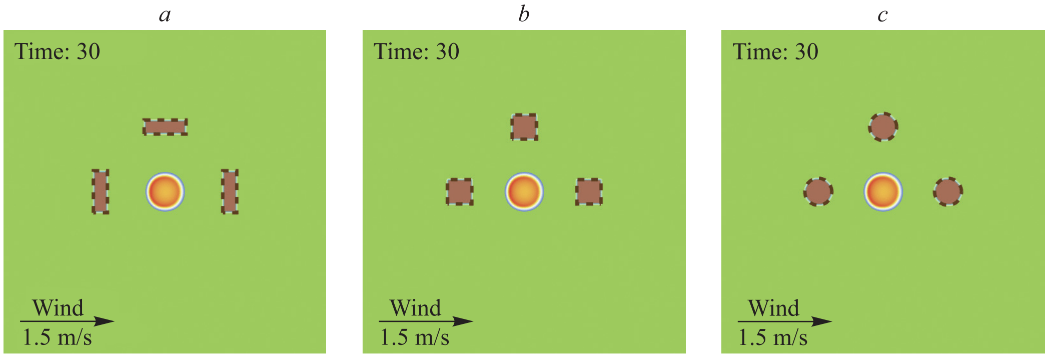

Fig. 5. Three variants of fuelbreak shapes at the moment of fire ignition (time point is 30): rectangular (*a*), quadratic (*b*) and circular (*c*) fuelbreak geometry

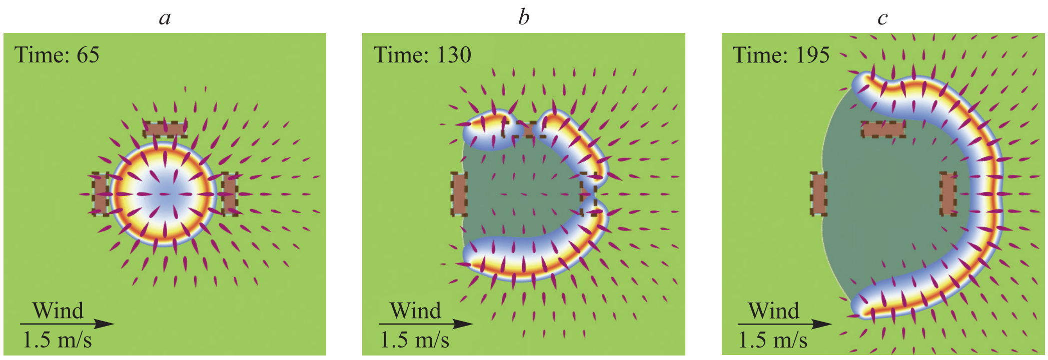

Fig. 6. Fire dynamics for the rectangular fuelbreak geometry at the following time points: 65 (*a*), 130 (*b*), 195 (*c*)

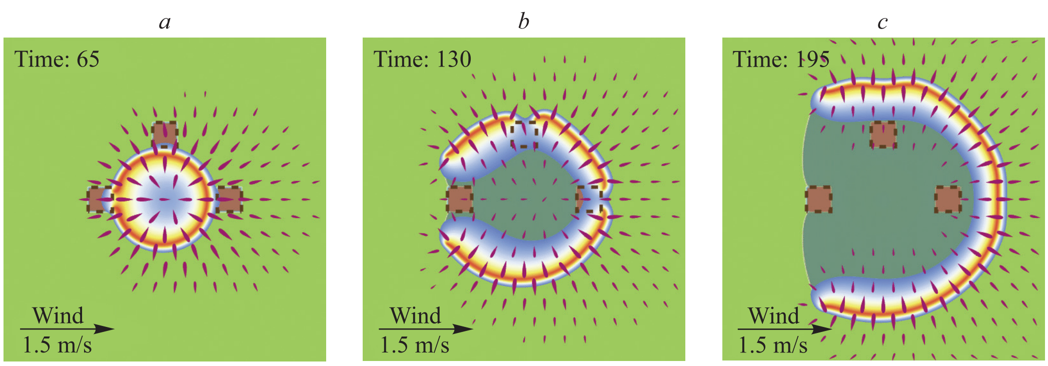

Fig. 7. Fire dynamics for the quadratic fuelbreak geometry at the following time points: 65 (*a*), 130 (*b*), 195 (*c*)

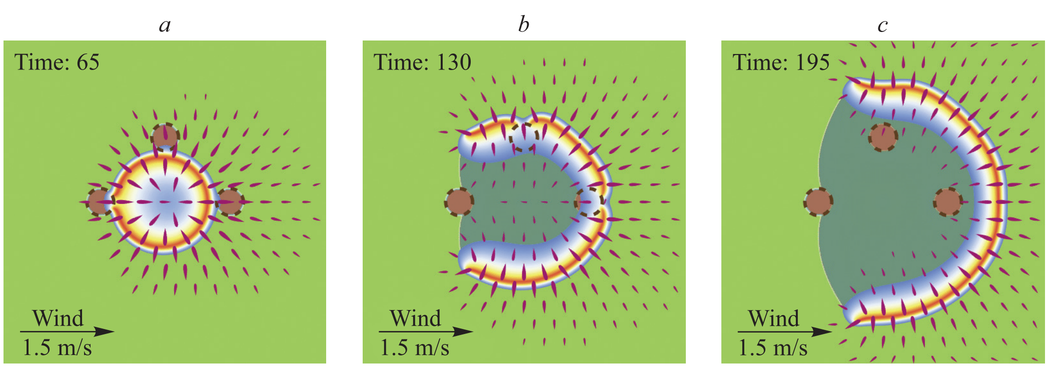

Fig. 8. Fire dynamics for the circular fuelbreak geometry at the following time points: 65 (*a*), 130 (*b*), 195 (*c*)

The following interpretation of the results seems to be justified. While passing the glades, the fire front breaks into independent parts, which go around them. In the direction opposite to the wind speed the propagation stops. Along the wind direction and «perpendicularly» to it, the autonomous parts of the fire front close again, and the fire spreads as a united front. There is a noticeable difference in the resulting configuration of the front isotherms after overcoming different forms of glades. The question whether these differences will grow in time, or whether the fronts will take the same configuration, requires a separate study.

Taking into account the influence of the wind speed

The influence of the wind speed on the nature of the forest fire spread is illustrated in fig. 9–11. In the given computational experiments, in terms of geometry, the case of circular fuelbreaks of a «small» size is considered. Figure 10 (the same as fig. 2) shows the calculation for the wind speed $V = 1.5$ m/s; fig. 9 and 11 show the results of two additional series of calculations, which differ from the version in fig. 10 only by the wind speeds V, which are equal to 1 and 2 m/s respectively.

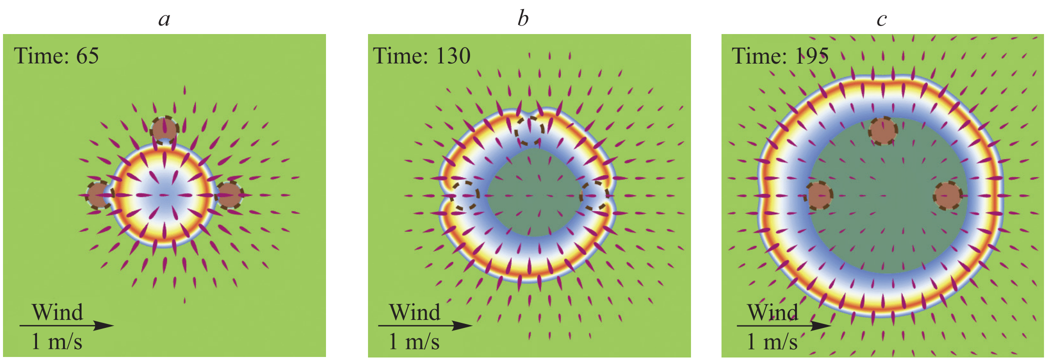

Fig. 9. Fire dynamics for the circular fuelbreaks at 1 m/s wind velocity at the following points: 65 (*a*), 130 (*b*), 195 (*c*)

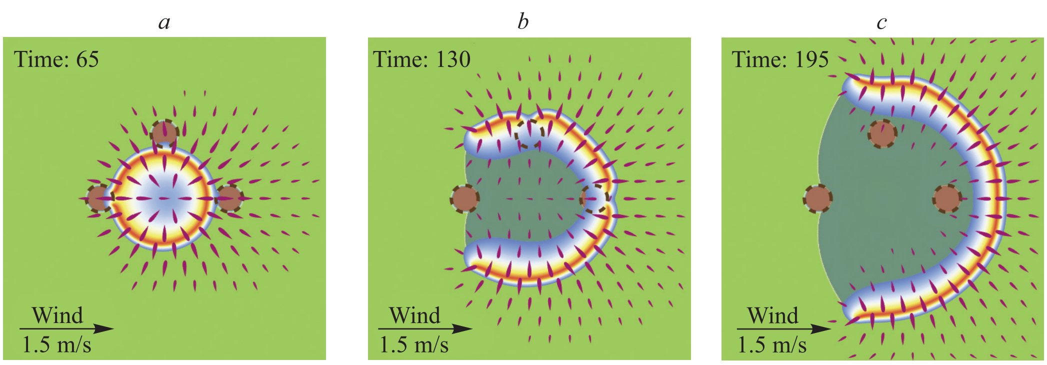

Fig. 10. Fire dynamics for the circular fuelbreaks at 1.5 m/s wind velocity at the following points: 65 (*a*), 130 (*b*), 195 (*c*)

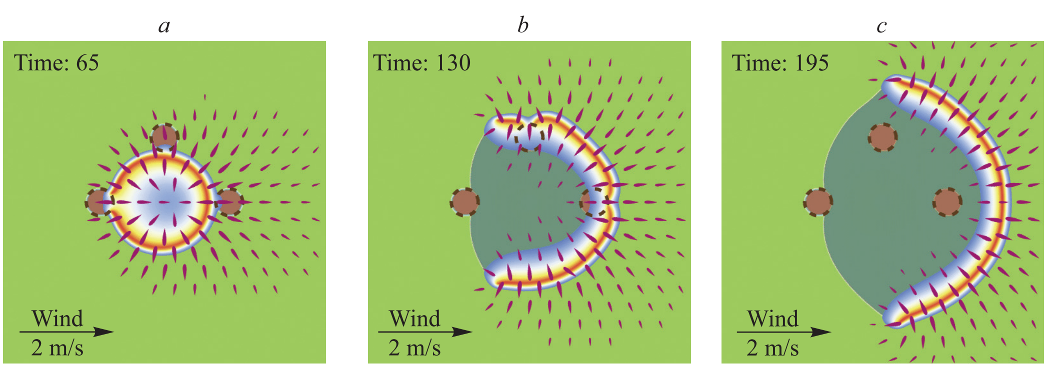

Fig. 11. Fire dynamics for the circular fuelbreaks at 2 m/s wind velocity at the following points: 65 (*a*), 130 (*b*), 195 (*c*)

Figure 9 is of particular interest. At low wind speeds, fire fronts overcome the glades in all directions, including the direction against the wind. It should also be noted that the width of the burning line in the direction of the wind is narrower than on the flanks, and in the rear this width is maximum. In fig. 9 at time 195 it is noticeable that the point of the minimum oxygen concentration is shifted to the right (to the direction of the wind), relative to the centre of the initial fire occurrence. The most likely reason is the influence of the convective transport due to the wind force.

Concluding the discussion of the results and illustrations of the distributions of temperature and bulk density of combustible forest materials, let us note that the developed software package can also calculate and save to a database [35] the distributions of the released water vapour [34], polluting gases, coal and ash. The corresponding spatial distributions and integral characteristics at control points in time can be visualised with maps, tables, and graphs of changes.

Conclusion

The article discusses the results of numerical experiments; the qualitative differences in the evolution and configuration of the fire front, the directions and intensities of the oxygen concentration gradients during the surface forest fire spread are identified and noted. Situations are considered when there are fuelbreaks of different shapes and sizes on the path of the fire front, moreover, for several typical variants of the wind speed in the forest canopy. Possible specific features of the controlled distributions of the process characteristics are shown.

Separately, we note the features of conducting computational experiments. In terms of the software performance, it should be noted that calculations are very time-consuming, each option is calculated on a «regular» laptop for several tens of hours, but at this stage optimisation and performance improvement, including *Wolfram Mathematica* tools for parallelising calculations, were not implemented. The possibilities of such technical solutions are obvious, because explicit approximations are used, the grid solution of each equation of the system can be calculated on a separate computing core. The current state of performance of the software complex suits the goals of its use, the main of which is filling collections of typical process scenarios for basic fragments of territories for typical environmental conditions and forests. The positive aspects of the developed software package are the ability to interrupt calculations at any time, visualise and analyse the intermediate results, change the model parameters and continue calculations from any saved time layer.

The authors have accumulated a large volume of results of calculations of the dynamics of forest fires varying in a wide range of parameters and initial conditions included in the model. We developed methodological and technical solutions for the use of artificial neural networks for geodata processing [32; 36; 37]. Based on the generated database of calculation results, we plan to make it possible to predict the dynamics of forest fires in real time using semi-empirical models [38] by extending them with intelligent data processing tools. The main part of such work will be the inclusion of neural networks in the complex: a) creation of test cases for training a neural network based on the database of numerical results of forest fires propagation; b) after training, the neural network would predict in real-time the propagation velocity of the fire contour depending on the categories of territories, climatic conditions, density of distribution of forest vegetation.

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