Investigation of Wind Velocity Impact on Forest Fire Spread Using Physical Based Computer Model

Valery Taranchuk, Dmitry Barovik

Belarusian State University
4 Nezavisimosti Ave., 220030 Minsk, Belarus
Taranchuk@bsu.by, BarovikD@gmail.com

Abstract. *The problem of computer modeling of two-dimensional surface forest fire spread is considered. The article describes the initial-boundary value problem in a form of a system of partial differential equations. Presented mathematical model of surface forest fires spread calculates the evolution of the temperature, of combustible forest materials, volume fractions of the multiphase reactive medium, mass concentration of components of a gas phase. The system of PDEs is solved numerically. Authors explicit numerical schemes with an adaptable locally uniform grid over coordinates and variable steps over time are used. Time steps are selected in accordance with stability conditions of the numerical scheme, and with the speeds of physical and chemical processes at each specific step. Examples illustrate the results of numerical experiments showing how fire front spreads in a forest with fuelbreaks in windy conditions. Qualitative differences in the geometry and dynamics of temperature density maps are shown for a range of wind velocity values.*

Keywords: *surface forest fire, wildland fire, physical and chemical processes of combustion, computer model, numerical method, heat and mass transfer equations, temperature density map, fire front dynamics, Wolfram Mathematica, fuelbreak, wind velocity, software.*

1 Introduction

Forest fires cause significant material and environmental damage. For example, according to the World Wildlife Fund (WWF) more than a billion animals died in bushfires started in Australia in September 2019

[1]. Experts of the Moody's analyst center at the beginning of 2020 calculated [2] economic damage from Australia's fires over 4.4 billion US dollars.

Problems associated with forest fires are important for many countries due to the fact that monitoring and management of forest fires require significant material costs. Therefore, the current task is to ensure the effectiveness of forest fire services with the help of mathematical methods and modern information technologies. The creation of appropriate computer models and software, their inclusion in the decision support systems for the prevention of emergency situations in forests and surrounding areas is required for reasonable, successful actions for the prevention, elimination of forest fires. The development of forest fires mathematical models started from 1940s but many problems have not been yet resolved [3, 4].

Forest fires are divided into underground fires, surface fires, passive crown fires, active crown fires (dependent from surface fire), running crown fires (independent from surface fires), and mass fires. The most common type of forest fire is a surface fire. It involves materials such as dry grass, fallen leaves and needles lying on the ground, shrubs, bushes and small hardwood trees. Surface fire is generally slow moving and flames can rise almost one to two meters high. As the surface fire intensifies by burning more material, when heavier bushes and medium size trees start burning then the flames may rise as high as five meters or more.

In accordance with scientific publications [5, 6] in this article we use the following classification of computer models of forest fires: empirical (statistical), semi-empirical, and theoretical (physical based).

Empirical (statistical) models calculate the rate of forest fire spread by searching for historical information of statistical correlation between fire propagation speed and some controlled parameters. Such an approach does not study the mechanism of the phenomenon; the results, strictly speaking, cannot be extended beyond the applicability of the statistics used, and even within them such a forecast is made only with a certain probability. The issues of development and examples of application of such models can be found in [7, 8].

In semi-empirical models general laws (conservation of energy, mass and amount of motion) are used to determine the characteristics of fire propagation. They are written in the form of simplified dependencies, and the corresponding coefficients are selected by generalizing the experimental information. Semi-empirical models are more adequate in comparison with empirical models. Development and generalization of traditional models of this type are proposed in [7, 8]. Semi-empirical models are adequate in situations similar to those in which experimental data were collected. Such models are much easier to verify than theoretical ones. Software realization of the proposed computer models of the above types, the technical aspects of their development and capabilities are described in [9].

Theoretical (physical based) models are based on the laws of continuum mechanics, other fundamental laws of physics and chemistry. Only this type of model describes the processes in dynamics taking into account general and local factors. The model can answer a very wide range of questions and solve problems for real cases with nonuniform distribution of parameters. Mathematical descriptions of theoretical models are given, as a rule, in the form of a system of partial differential equations (PDEs).

Professor Grishin A.M. [10] created one of the most general theoretical models for the spread of forest and peat fires. A number of researchers, including the authors of this work, take the Grishin's model as a basis and adopt it for practical use [11]. The application of the model for crown forest fires modeling can be found in article [12]. Representative results of simulation of crown forest fires are given in articles [13, 14]. The above-mentioned papers illustrate several typical fire propagation scenarios and fire fighting activities.

In current article we demonstrate the 2D model of forest fire spread in case of circular fuelbreaks presence. We show the impact of wind velocity on the speed and characteristics of fire spread.

2 Mathematical Model of Surface Forest Fires Spread

Basic concepts. Presented mathematical model of forest fires spread calculates the evolution of the following values: T—temperature (in Kelvins) of combustible forest materials (CFM); $\varphi_j,\ j = 1, 2, 3, 4$—volume fractions of the multiphase reactive medium, where φ_1 corresponds to a dry organic substance, φ_2—water in a liquid-drop state combined with CFM, φ_3—coke (condensed pyrolysis product), φ_4—mineral part of CFM (ash); $c_\nu,\ \nu = 1, 2, 3$—mass concentration of components of a gas phase, where c_1 corresponds to oxygen (O_2), c_2—to combustible gases (combustible pyrolysis product components), c_3—mixes of other gases (inert components of air, water vapor, inert products of reactions of pyrolysis, coke burning and of combustible gases oxidation).

Among physical and chemical processes of CFM burning, the following are defined: the heat supply due to convection, heat conductivity and radiation, forest fuel heating, drying and pyrolysis, burning of gaseous, disperse and solid products of pyrolysis. The derivation of the equations, the model justification, the numerical scheme and the organization of calculations are given in the publications [11, 12, 15].

Relatively to unknown functions $\varphi_j (j = 1, 2, 3, 4)$, $c_\nu (\nu = 1, 2, 3)$ and T, which depend on time and spatial coordinates, we formulate the initial-boundary value problem in the form of the following system of PDEs:

$$\frac{\partial \varphi_1}{\partial t} = \Phi_{\varphi 1}(\varphi_1, T), \qquad \frac{\partial \varphi_2}{\partial t} = \Phi_{\varphi 2}(\varphi_2, T), \tag{1}$$

$$\frac{\partial \varphi_3}{\partial t} = \Phi_{\varphi 3}(\varphi_1, \varphi_3, c_1, c_2, T), \qquad \frac{\partial \varphi_4}{\partial t} = 0, \tag{2}$$

$$\frac{\partial c_1}{\partial t} + V_x \frac{\partial c_1}{\partial x} - \frac{D_T}{\rho_5}\left(\frac{\partial}{\partial x}(\rho_5 \frac{\partial c_1}{\partial x}) + \frac{\partial}{\partial y}(\rho_5 \frac{\partial c_1}{\partial y})\right) = \Phi_{c1}(\varphi_1, \varphi_2, \varphi_3, c_1, c_2, T), \tag{3}$$

$$\frac{\partial c_2}{\partial t} + V_x \frac{\partial c_2}{\partial x} - \frac{D_T}{\rho_5}\left(\frac{\partial}{\partial x}(\rho_5 \frac{\partial c_2}{\partial x}) + \frac{\partial}{\partial y}(\rho_5 \frac{\partial c_2}{\partial y})\right) = \Phi_{c2}(\varphi_1, \varphi_2, \varphi_3, c_1, c_2, T), \tag{4}$$

$$\frac{\partial T}{\partial t} + \left(V_x \rho_5 c_{p5} \frac{\partial T}{\partial x} - \lambda_T (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2})\right) / \left(\rho_5 c_{p5} + \sum_{j=1}^{4} \rho_j \varphi_j c_{pj}\right) = \Phi_T, \tag{5}$$

$$\rho_5 = \frac{\rho_\infty T_\infty}{M_\infty T (c_1/M_1 + c_2/M_2 + c_3/M_3)}, \qquad c_3 = 1 - c_1 - c_2. \tag{6}$$

The defining functions are:

$$\Phi_{\varphi 1}(\varphi_1, T) = -R_1/\rho_1, \qquad \Phi_{\varphi 2}(\varphi_2, T) = -R_2/\rho_2, \tag{7}$$

$$\Phi_{\varphi 3}(\varphi_1, \varphi_3, c_1, c_2, T) = \frac{\alpha_c R_1}{\rho_3} - \frac{M_c}{M_1}\frac{R_3}{\rho_3}, \tag{8}$$

$$\Phi_{c1}(\varphi_1, \varphi_2, \varphi_3, c_1, c_2, T) = \left(R_{51} - c_1 Q - \frac{\alpha}{c_{p5}\Delta h}(c_1 - c_{1\infty})\right) / \rho_5, \tag{9}$$

$$\Phi_{c2}(\varphi_1, \varphi_2, \varphi_3, c_1, c_2, T) = \left(R_{52} - c_2 Q - \frac{\alpha}{c_{p5}\Delta h}(c_2 - c_{2\infty}) \right) / \rho_5, \quad (10)$$

$$\Phi_T(\varphi_1, \varphi_2, \varphi_3, c_1, c_2, T) = \frac{q_5 R_5 - q_2 R_2 + q_3 R_3 - \alpha(T - T_\infty)/\Delta h - 4\kappa_R \sigma T^4}{\rho_5 c_{p5} + \sum\limits_{j=1}^{4} \rho_j \varphi_j c_{pj}}, \quad (11)$$

$$Q = (1 - \alpha_c) R_1 + R_2 + \frac{M_C}{M_1} R_3. \quad (12)$$

$$R_1 = k_{01} \rho_1 \varphi_1 \exp(-E_1/RT), \qquad R_2 = k_{02} T^{-1/2} \rho_2 \varphi_2 \exp(-E_2/RT), \quad (13)$$

$$R_3 = k_{03} s_\sigma \varphi_3 \rho_5 c_1 \exp(-E_3/RT), \quad (14)$$

$$R_{51} = -R_3 - \frac{R_5 M_1}{2M_2}, \qquad R_{52} = (1 - \alpha_c)\nu_G R_1 - R_5, \quad (15)$$

$$R_5 = \rho_5 \min(c_2, \frac{M_2}{2M_1} c_1) k_{CO} \exp(-E_{CO}/RT). \quad (16)$$

Here t is the time; V_x is an equilibrium wind speed vector; T_∞ is unperturbed ambient temperature; $\rho_j,\ j = 1, 2, 3, 4$ is the j^{th} phase density; ρ_5 is the density of a gas phase (a mix of gases); ρ_∞ is unperturbed density of a mix of gases (air density); $c_{1\infty}$ and $c_{2\infty}$ are mass concentrations of oxygen and combustible gases in unperturbed atmosphere; $M_\nu,\ \nu = 1, 2, 3$ are molecular masses of gas phase components; M_C is a molecular mass of carbon, M_∞ is a molecular mass of air; $c_{pj},\ j = 1, 2, 3, 4$ is the j^{th} phase thermal capacity; c_{p5} is thermal capacity of a gas phase; Q is a mass rate of generation gas phase; λ_T is turbulent thermal conductivity; D_T is the diffusion coefficient; q_2, q_3 and q_5 are heat effects of processes of evaporation, of burning of the condensed fuel and of gaseous combustible pyrolysis products accordingly; Δh is a height of forest fuel (CFM); α is a coefficient of heat exchange between the atmosphere and a forest canopy; κ_R defines integrated absorption coefficient; σ is the StefanBoltzmann constant; R_1 is a mass rate of reaction of dry CFM pyrolysis (chemical decomposition of substance by heating with allocation of combustible gases), R_2 is a mass rate of reaction of moisture evaporation from CFM (drying), R_3 is a mass rate of reaction of coke burning; R_{51}, R_{52} are mass rates of generation (disappearance) of oxygen, combustible gases; R_5 is a mass rate of reaction of burning (oxidation) of combustible gases; k_{01}, k_{02}, k_{03}, k_{CO} are pre-exponential factors of chemical reactions, E_1, E_2, E_3, E_{CO} are the activation energies of chemical reactions, R is the universal gas constant, s_σ defines specific surface of the condensed product of pyrolysis (of coke), α_c is the coke value of CFM, ν_G is a proportion of gaseous combustible pyrolysis products.

3 Initial and Boundary Conditions

Initial and boundary conditions. Initial distributions of volume fractions φ_j, of mass concentrations c_ν and of temperature T are defined in a whole domain of a solution. Lets define the domain as G, and its boundary as B. The domain G can be divided by three subdomains $G = G_{fire} \cup G_- \cup G_+$. These subdomains are not necessarily simply connected, their mutual geometry can be quite complex, for example, for multiple spot fires. G_- and G_+ indicate burnt and unburned areas removed from fire zone to an adequate distance (these subdomains are characterized by unperturbed values $c_{1\infty}$, $c_{2\infty}$ and T_∞). In fire area G_{fire} initial distributions of values $\varphi_j (j = 1, 2, 3, 4)$, $c_\nu(\nu = 1, 2, 3)$ and T must be "self-consistent", because there are certain physical connections between all of these values that must be taken into account. These issues are rather complex and require separate discussion [12]. Initial distributions in burnt G_- and unburned G_+ areas are given as follows:

$$T|_{t=0}(G_- \cup G_+) = T_\infty, \tag{17}$$

$$c_1|_{t=0}(G_- \cup G_+) = c_{1\infty}, \qquad c_2|_{t=0}(G_- \cup G_+) = c_{2\infty}, \tag{18}$$

$$c_3|_{t=0}(G_- \cup G_+) = 1 - c_{1\infty} - c_{2\infty}, \tag{19}$$

$$\varphi_1|_{t=0}(G_+) = \frac{\rho_0}{\rho_1}, \qquad \varphi_2|_{t=0}(G_+) = (1-\zeta)W\frac{\rho_0}{\rho_2} \tag{20}$$

$$\varphi_3|_{t=0}(G_+) = 0, \qquad \varphi_4 = 0 \tag{21}$$

$$\varphi_1|_{t=0}(G_-) = 0, \qquad \varphi_2|_{t=0}(G_-) = 0, \qquad \varphi_3|_{t=0}(G_-) = \alpha_c\frac{\rho_0}{\rho_3}. \tag{22}$$

It is supposed than in G_- area forest fuel is fully burnt; the bulk densities ρ_0 of typical layer of CFM, phase densities $\rho_j(j = 1, 2, 3, 4)$, W moisture content of forest fuel and ash content ζ of combustible forest materials can be heterogeneous. All these distributions in the area of modeling must be provided as functions of coordinates. At the boundary B of the modeling domain G we define "weak" boundary conditions:

$$\frac{\partial T}{\partial n}|_B = 0, \qquad \frac{\partial c_1}{\partial n}|_B = 0, \qquad \frac{\partial c_2}{\partial n}|_B = 0. \tag{23}$$

4 The Results of Modeling Fires in Forests with Circular Fuelbreaks at Different Wind Velocities

The system of PDEs described above was solved numerically using the Wolfram *Mathematica* system [16, 17]. We used authors explicit numerical schemes with an adaptable locally uniform grid over coordinates and variable steps over time. Time steps were chosen in accordance with stability conditions of the numerical scheme, and with the speeds of physical and chemical processes at each specific step [12, 18].

The strongest change in environmental condition parameters occurs in the zone called fire front, which propagates at some speed by the territory, covered with forest, and is visually observed as a zone captured by a flame. As a rule the effects of smoke generation over a big territory and clouds formation over a fire zone, because of condensation of the water vapor released during combustible forest materials burning, take place. We attempt here to describe the various key components that characterize fuelbreaks, evaluate their use, and discuss alternatives to traditional fuelbreak approaches. A fuelbreak is "a strategically located wide block, or strip, on which a cover of dense, heavy, or flammable vegetation has been permanently changed to one of lower fuel volumes or reduced flammability" [19]. The effectiveness of fuelbreaks remains a subject of debate within and outside of the fire management community. There are many reasons for this broad range of opinion, among them that objectives can vary widely, fuelbreak prescriptions (width, amount of fuel reduction, maintenance standards) may also vary, they can be placed in many different fuel conditions, and may be approached by wildland fires under a variety of normal to extreme weather conditions.

Lets consider the square area (20×20 meters) of the forest. The "burning" starts at the origin of the coordinate system. For simplicity, the direction of the wind V_x in the forest canopy is along the axis Ox (from left to right on the graphs given). In this case, in the direction of the wind, against the wind and perpendicularly (on one of the flanks) there are areas with no combustible vegetation (fuelbreaks). Graphical visualization of the described configuration and written expressions are given on figures 1–3.

Background layer of the figures 1–3 shows the density of forest combustible material. Green color represents forest which is not affected by

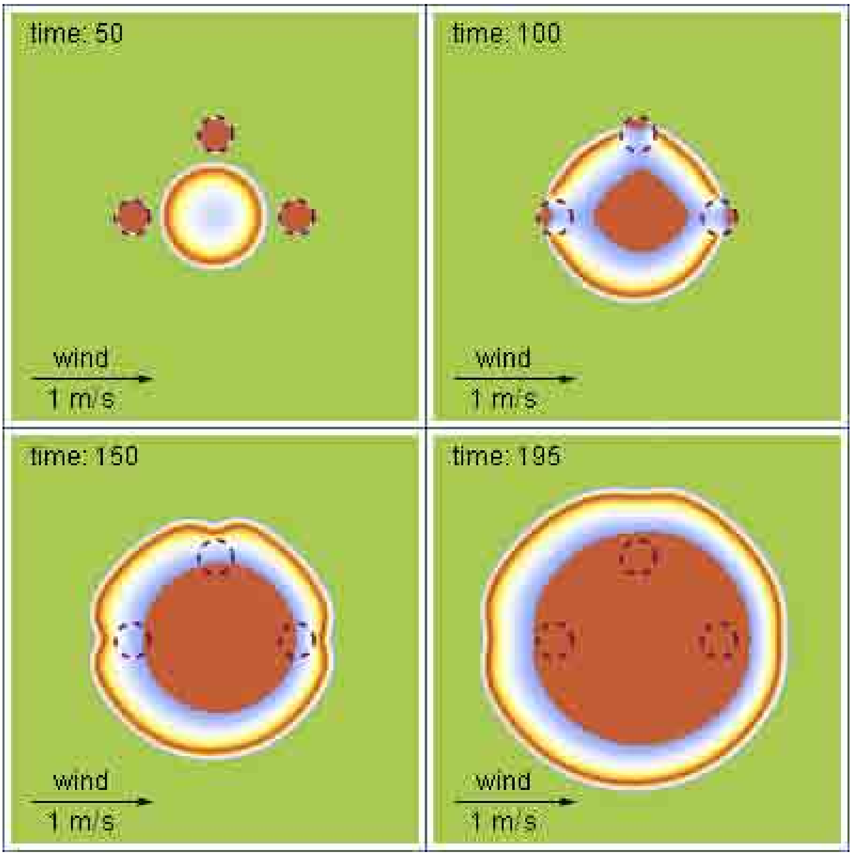

Figure 1: Fire spreads through circular fuelbreaks at wind velocity 1.0 m/s

fire, and brown color is used for areas with a complete lack of combustible material (glades and completely burned forest). Foreground layer of the drawings displays color gradient maps of temperature distribution in the combustion zone. Every figure shows the development of fire at four moments in time: during the "rounding" of the fuelbreaks, when the fronts are open, and after the fuelbreaks are passed through by fire front. Figures 1–3 differ only by the wind velocity: 1.0, 1.5 and 2.0 meters per second, respectively.

Following values are used for the modeling: $W = 10\%$, $\rho_0 = 5\ kg/m^3$, $\Delta h = 0.1$ m, $T_\infty = 304$ K, $\rho_1 = 500\ kg/m^3$, $\rho_2 = 1000\ kg/m^3$, $\rho_3 = 200\ kg/m^3$, $\rho_4 = 200\ kg/m^3$, $\rho_\infty = 1.15\ kg/m^3$, $c_{1\infty} = 0.23$, $c_{2\infty} = 0$, $M_1 = 32$, $M_2 = 28$, $M_3 = 29$, $M_C = 12$, $M_\infty = 29$, $c_{p1} = 2000\ J/(kg \cdot K)$, $c_{p2} = 4180\ J/(kg \cdot K)$, $c_{p3} = 900\ J/(kg \cdot K)$, $c_{p4} = 1000\ J/(kg \cdot K)$, $c_{p5} =$

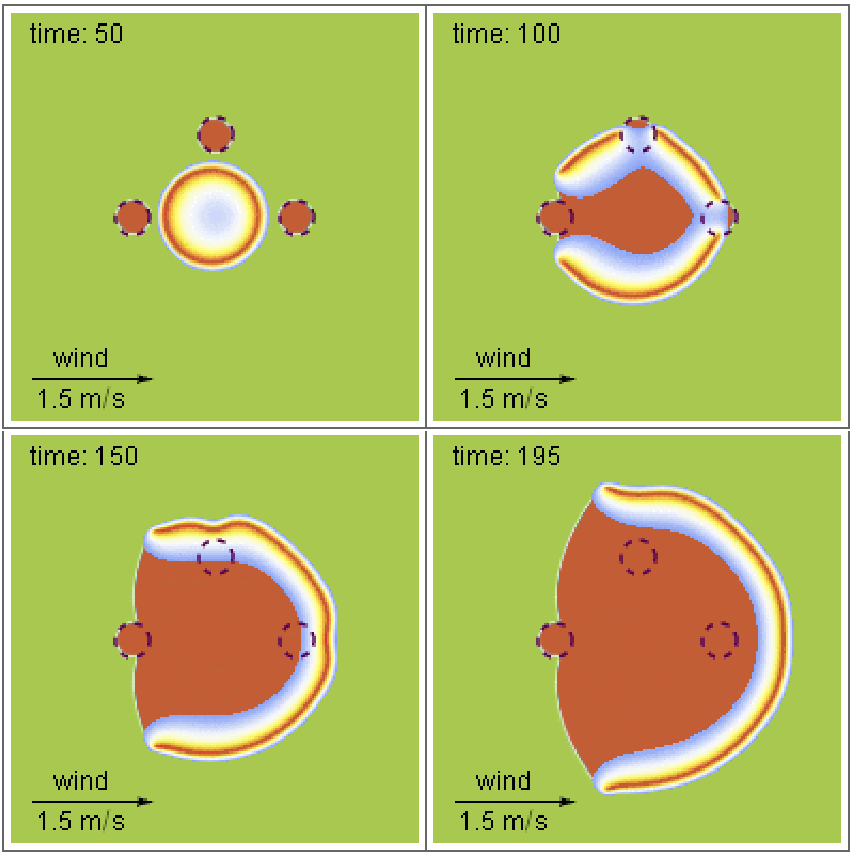

Figure 2: Fire spreads through circular fuelbreaks at wind velocity 1.5 m/s

1000 $J/(kg \cdot K)$, $q_2 = 3 \cdot 10^6$ J/kg, $q_3 = 1.2 \cdot 10^7$ J/kg, $q_5 = 10^7$ J/kg, $\lambda_T = 1000 J/(m \cdot s \cdot K)$, $D_T = 1.5 m^2/s$, $\alpha = 100$ $W/(m^2 \cdot K)$, $\alpha_c = 0.1$, $v_G = 0.8$, $\kappa_R = 1.5$ m^{-1}, $S_\sigma = 1000$ m^{-1}, $E_1/R = 9400$ K, $E_2/R = 6000$ K, $E_3/R = 10000$ K, $E_{CO}/R = 11649$ K, $k_{01} = 3.63 \cdot 10^4$ s^{-1}, $k_{02} = 6 \cdot 10^5$ $K^{0.5} s^{-1}$, $k_{03} = 1000$ s^{-1}, $k_{CO} = 7.05 \cdot 10^6$.

The results of three wind velocities of modeling are presented. The fire starts spreading, reaches the glades and begins to curve around them. The results show that different variants of the further development of the process are possible. At low wind velocity all fire fronts close again regardless of wind direction (figure 1). When wind velocity increases above 1.5 m/s then one front of the fire, which is opposite to the wind direction, doesnt close (figures 2–3). When the wind is strong enough, then the fire propagates only in the wind direction. Figure 3 confirms the existence of a direct dependence of the speed of fire front propagation on the equilibrium wind velocity in the forest canopy.

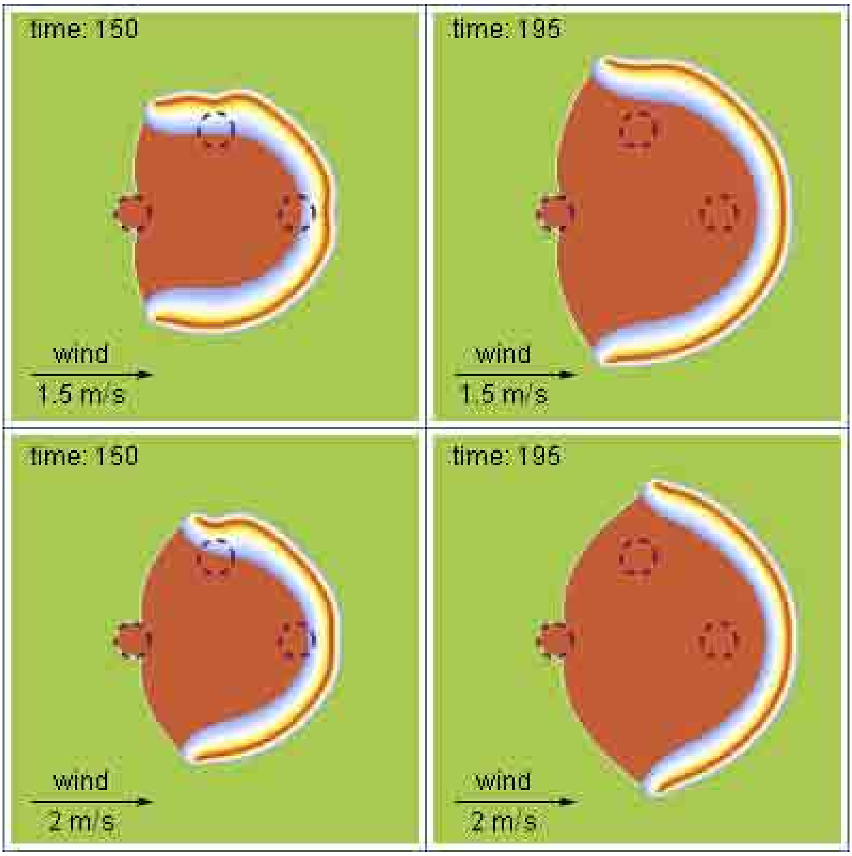

Figure 3: Acceleration of fire front spread due to an increase in wind velocity from 1.5 m/s to 2 m/s

There is a clear theoretical basis for concluding that fuelbreaks will alter fire behavior in ways amenable to limiting both the sizes of wildland fires and reducing the severity of damage from them. Combining fuelbreaks with area-wide fuel treatments in adjacent areas can reduce the size and intensity of wildland fires.

5 Conclusion

The results of the computational experiments illustrate some specific features of the simulated processes of surface forest fires; confirm the variety of different scenarios for fire fronts propagation. It is highly important to continue researches and to clarify the defining variables and functions of the mathematical model.

The figures show only two (temperature and bulk density of dry forest combustible materials) of the six values calculated by the model. The model also allows to calculate the emission of polluting gases, the dynamics of the emerging wind, and other processes that are important from a practical point of view [20]. The unresolved issue is the complexity of the calculations, the impossibility of using the model in real time [21].

References

[1] *wwf.org.ua* Statement from WWF-Australia on Australias bushfire emergency. URL: www.wwf.org.au/news/news/2020/statement-from-wwf-australia-on-australia-s-bushfire-emergency (2020).

[2] *theguardian.com* Economic impact of Australias bushfires set to exceed $4.4bn cost of Black Saturday. URL: www.theguardian.com/australia-news/2020/jan/08/economic-impact-of-australias-bushfires-set-to-exceed-44bn-cost-of-black-saturday (2020).

[3] *Frangieh N. [et al]* Wildfires front dynamics: 3D structures and intensity at small and large scales. Combustion and Flame **211** (2020) 54–67. DOI: 10.1016/j.combustflame.2019.09.017

[4] *Perminov V., Goudov A.* Mathematical modeling of forest fires initiation, spread and impact on environment. International Journal of GEOMATE **13** (35) (2017) 93–99. DOI: 10.21660/2017.35.6704

[5] *Pastor E. [et al]* Mathematical models and calculation systems for the study of wildland fire behaviour. Progress in Energy and Combustion Science **29** (2003) 139–153.

[6] *Barovik D.V., Taranchuk V.B.* Sostoyanie problemy i rezul'taty komp'yuternogo prognozirovaniya rasprostraneniya lesnyh pojarov. Vestnik BGU. Seriya 1, Fizika, Matematika, Informatika (2011) 78–84 [in Russian].

[7] *Barovik D.V., Taranchuk V.B.* Adaptaciya modeli Rotermela dlya realizacii v programmnom komplekse prognoza rasprostraneniya lesnyh pojarov. Nauchnyi internet jurnal Tehnologii tehnosfernoi bezopasnosti **6** (40) (2011) 1–8 [in Russian].

[8] *Barovik D.V., Taranchuk V.B.* O razvitii metodiki Rotermela i realizacii dvumernoi komp'yuternoi modeli prognoza rasprostraneniya lesnyh pojarov. VESNIK Vicebskaga dzyarjaunaga universiteta **6** (66) (2011) 5–11 [in Russian].

[9] *Barovik D.V., Korzyuk V.I., Taranchuk V.B.* Metodicheskie i algoritmicheskie osnovy programmnogo kompleksa "Raschet i vizualizaciya dinamiki lesnogo pojara". Chrezvychainye situacii: preduprejdenie i likvidaciya **2**(30) (2011) 22–33 [in Russian].

[10] *Grishin A.M.* Mathematical modeling of forest fires and new methods of fighting them. Tomsk : Publishing House of the Tomsk State University, 1997. 390 p. Translated by Marek Czuma, L. Chikina and L. Smokotina; edited by Frank Albini.

[11] *Barovik D.V., Taranchuk V.B.* Ob osobennostyah adaptacii matematicheskih modelei vershinnyh verhovyh lesnyh pojarov. Vestnik BGU. Seriya 1, Fizika, Matematika, Informatika (2010) 138–143 [in Russian].

[12] *Barovik D.V., Taranchuk V.B.* Mathematical modelling of running crown forest fires. Mathematical Modelling and Analysis **15** (2) (2010) 161–174. DOI: 10.3846/1392-6292.2010.15.161–174.

[13] *Barovik D.V., Taranchuk V.B.* Crown Forest Fire Mathematical Model Realization in Wolfram Mathematica. Vol. Mathematical Modeling in Physics, Civil Engineering, Economics and Finance (2011) 5–15.

[14] *Barovik D.V., Taranchuk V.B.* Results of Crown Forest Fires Mathematical Modelling. Computer Algebra Systems in Teaching and Research. Vol. Mathematical Modeling in Physics, Civil Engineering, Economics and Finance (2011) 16–22.

[15] *Barovik D.V., Korzyuk V.I., Taranchuk V.B.* K obosnovaniyu matematicheskih modelei nizovyh lesnyh pojarov. Trudi instituta matematiki **21**(1) (2013) 3–14 [in Russian].

[16] *Taranchuk V.B., Barovik D.V.* O sredstvakh Wolfram Mathematica dlya rasparallelivaniya vychisleniy v komp'yuternykh modelyakh lesnykh pozharov. Veb-programmirovanie i internet-tekhnologii WebConf 2015. Minsk: Belorusskiy gosudarstvennyy universitet (2015) 108–109 [in Russian].

[17] *Taranchuk V.B.* Osnovy programmirovaniya na yazyke Wolfram : ucheb. materialy dlya studentov fak. prikladnoi matematiki i informatiki spec. 1-31 03 04 "Informatika", Minsk, BGU, 2015 [in Russian].

[18] *Barovik D.V., Korzyuk V.I., Taranchuk V.B.* On the correctness of a mathematical model of ground forest fires. Doklady Natsional'noy akademii nauk Belarusi **57**(4) (2013) 5–9 [in Russian].

[19] *Barovik D.V., Taranchuk V.B.* Numerical Modelling of Surface Forest Fire Spread in Nonuniform Woodland. Computer Algebra Systems in Teaching and Research (CASTR 2019). Vol. VIII (2019) 159–168.

[20] *Taranchuk V.B., Barovik D.V.* Komp'yuternoe modelirovanie lesnykh pozharov. Nauka, innovatsii, investitsii: sbornik materialov 2-go Belorussko-Latviyskogo foruma. Minsk: Belorusskiy natsional'nyy tekhnicheskiy universitet (2014) 73–75. [in Russian]

[21] *Barovik D.V., Taranchuk V.B.* Modelirovanie protsessov rasprostraneniya nizovykh lesnykh pozharov pri nalichii polyan na puti ognya. Matematicheskie metody v tekhnike i tekhnologiyakh MMTT, Vol 12, Part 1 (2017) 109–113 [in Russian].

Alexander N. Prokopenya
Agnieszka Gil-Świderska
Marek Siłuszyk (Eds.)

Computer Algebra Systems in Teaching and Research

Volume IX

Siedlce University of Natural Sciences and Humanities

Siedlce 2020

Cover designed by Paweł Trojanowski

ISBN 978-83-66541-17-7

Uniwersytet Przyrodniczo-Humanistyczny w Siedlcach

Instytut Matematyki

08-110 Siedlce, ul. 3-Maja 54,

tel. +48 25 643 1103, e-mail: imif@uph.edu.pl

Contents

I. Mathematical Modeling and Differential Equations