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# Surface Forest Fires Modelling: Temperature and Oxygen Dynamics near Fuelbreaks

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**Abstract.** The problem of computer modelling of the spread of surface forest fires in a twodimensional formulation is considered. The results of numerical experiments investigating possible scenarios of how fire spreads in different directions and its behaviour near fuelbreaks are presented. Several qualitative differences in geometry and dynamics of temperature density maps and oxygen concentration stream plots are determined and illustrated with interactive multidimensional graphics for various shapes and sizes of fuelbreaks, including the demonstration of the influence of the equilibrium wind speed in the forest canopy on the fire spread over the territory. Possible variations of the fire front movement in the direction of wind velocity and against it are identified and explained using representative examples.

**Keywords:** surface forest fire, wildfire, mathematical model, fire front dynamics, fuelbreak shape, fuelbreak size, wind velocity, software, oxygen concentration stream plot

### 1 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 (Dvornik et al., 2021). 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 (Morvan, 2019; Sullivan, 2009a,b,c). In particular, there is no convincing proof for the kinetics of physicochemical transformations and reactions used in the models. There are different, sometimes contradictory, models of turbulence processes in the gas phase. 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 of the 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. 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 (Matsuoka et al., 2020)). In this work, the features of forest fires spread in case of the inclusion of clearings (fuelbreaks (Antonov et al., 2020; Frangieh et al., 2021; Perminov and Marzaeva, 2020)) of various shapes and sizes are modelled, visualised, and discussed. The results of the analysis of temperature distribution in fire fronts, as well as oxygen flows, caused precisely by the inhomogeneities of the location of combustible vegetation in the area are presented. The influence of the direction and intensity of the wind is also taken into account.

Forest fires are a multiscale phenomenon both in space and time. The article (Frangieh et al., 2020) suggests three scales: flame, wildfire, and fire regime. On the first scale, a fire can be considered at the level of the combustion process (flame). Firefighters use the so-called triangle at this level: (Oxygen/Combustible Material/Heat). All three components are necessary for combustion. If any of these is removed by special action, then the combustion will stop. The flame level is characterised by a scale of centimetres in space and minutes in time. When the scale increases, a forest fire can be considered at the level of a natural disaster. We can define the triangle: (Topography/Forest Fuel/Weather). For example, the severity of fire depends on the topography (plain or slope). Litter, branches, bushes, and trees differ in the ability to ignite and burn; weather conditions, in particular, wind or rain influence does not require explanation. On the wildland fire scale, distances are calculated in kilometres and time is measured in hours or days. On the fire regime scale, forest fires can be considered not as a disaster, but as natural evolutionary adaptation: (Ignition/Vegetation/Climate). Some types of trees and shrubs need fire to germinate seeds. Cones and fruits of some types of trees can open to release seeds only after the heat of the fire physically melts the resin. There are some shrubs and annual plants, the trigger for the germination of seeds of which are chemical signals of the smoke of charred plant substances. Such seeds can remain in the soil for decades until they are awakened by a forest fire. Years and hundreds of kilometres are considered on this scale.

Most of the currently used computer models of forest fires, as a rule, set as their ultimate goal the answer to the question, what are the velocities and directions of the spread of forest fires at the macro level. At this scale, the velocity is determined by comparing the positions of the fronts of burned forest regions at successive time points. The novelty of this work is the emphasis on the study of not only the areas of burnt vegetation, but also on related factors and causal processes that can be detected in specific areas. Here we study the dynamics of the appearance (or loss) of gases, changes in their position and temperature. Physicochemical processes of combustion and pyrolysis, heating and evaporation of liquids from wood micropores (Pushpa et al., 2021; Shafiq et al., 2021), convective and buoyancy-driven flow of gases (Djebali et al., 2021), thermal radiation, and other factors are taken into account. At the same time, emphasis is placed on the method of analysis and interpretation of results implemented by the use of cognitive graphics, which makes it possible to establish new qualitative features of the processes. By visualising the oxygen concentration gradient lines superimposed over the temperature isolines and the density distribution of combustible vegetation, it is possible to recognize trends in the movement of fire fronts on a smaller scale. It becomes possible to determine the influence of such factors as the presence, size, and shape of fuelbreaks, and wind velocities on the speed and direction of the fire front.

In the presented research, the theoretical model of professor A.M. Grishin (1997) 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 (Kuleshov et al., 2019; Perminov and Marzaeva, 2020), including the authors of this work, use Grishin's descriptions as a basis and modify them for practical use (Barovik and Taranchuk, 2010), ensuring that the specific conditions of the territories and climate are taken into account.

According to the existing reviews (Sullivan, 2009a,b,c), mathematical (computer) models of forest fires are usually classified as physical, semi-empirical (including statistical), and simulation. The authors of this article use a physical model describing processes in the form of a system of partial differential equations of mathematical physics. In some aspects, the tools used are special: modelling and visualisation are performed in the computer algebra system Wolfram Mathematica, the results are partly stored in a relational database, partly in files. The implemented numerical methods are almost traditional, but we use adaptable grids both in space and in time. This allows the authors, in the absence of the possibility of using large computing power, to perform calculations and visualisation of the results on a regular personal computer.

### 2 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 (Kuznetsov et al., 2019): heat supply caused by convection, thermal conductivity, and radiation; evaporation of water from forest fuel due to heating; decomposition of dry organic matter of forest fuel into components, combustion of gaseous and afterburning of solid pyrolysis products. The corresponding mathematical description implies the need to calculate the area distributions and the dynamics of the following values: T is the temperature of continuous multiphase reacting medium measured in Kelvins;  $\varphi_j$  (j = 1, 2, 3, 4) are volume fractions of components of forest fuel material, where  $\varphi_1$  denotes to dry organic matter of forest fuel,  $\varphi_2$  is water contained in vegetation in bound and free forms,  $\varphi_3$  is condensed pyrolysis product,  $\varphi_4$  is non-combustible mineral part (ash) of forest fuel;  $c_{\nu}$  ( $\nu = 1, 2, 3$ ) are relative mass concentrations of components of a gaseous phase, where  $c_1$  corresponds to the oxygen,  $c_2$  to combustible gases arising in

the process of thermal decomposition,  $c_3$  is used for a mixture of other non-combustible gases, including water vapour, resulted by drying, the carbon dioxide released during the afterburning of coke and oxidation of combustible gases, inert components of the air mixture and products of pyrolysis and combustion reactions.

The functions T,  $\varphi_1$ ,  $\varphi_2$ ,  $\varphi_3$ ,  $\varphi_4$ ,  $c_1$ ,  $c_2$ ,  $c_3$  depend on both time t and spatial coordinates x and y. Surface forest fire model is formulated as an initial-boundary value problem in the form of a system of partial differential equations (1)–(5). Initial and boundary conditions are given in (Barovik and Taranchuk, 2010; Barovik et al., 2013).

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

$$\frac{\partial c_1}{\partial t} + (V, gradc_1) - \frac{1}{\rho_5} div(\rho_5 D_T gradc_1) = \Phi_{c1}, \tag{2}$$

$$\frac{\partial c_2}{\partial t} + (V, gradc_2) - \frac{1}{\rho_5} div(\rho_5 D_T gradc_2) = \Phi_{c2},\tag{3}$$

$$\frac{\partial T}{\partial t} + \frac{\rho_5 c_{p5}(V, gradT) - div(\lambda_T gradT)}{\rho_5 c_{p5} + \sum_{j=1}^4 \rho_j \varphi_j c_{pj}} = \Phi_T, \tag{4}$$

$$\sum_{\nu=1}^{3} c_{\nu} = 1, \quad \rho_{5} = \frac{\rho_{\infty} T_{\infty}}{M_{\infty} T} \left( \sum_{\nu=1}^{3} \frac{c_{\nu}}{M_{\nu}} \right)^{-1}.$$
 (5)

Let us note that the right-hand sides of differential equations (1)–(4) represent functions depending on the calculated variables. In particular,  $\Phi_{\varphi_1}$  depends on  $\varphi_1$  and T, the function  $\Phi_{\varphi_2}$  depends on  $\varphi_2$  and T, and  $\Phi_{\varphi_3}$  depends on  $\varphi_1$ ,  $\varphi_3$ ,  $c_1$ ,  $c_2$ , and T.  $\Phi_{c1}$ ,  $\Phi_{c2}$  and  $\Phi_T$  depend on all variables  $\varphi_1$ ,  $\varphi_2$ ,  $\varphi_3$ ,  $c_1$ ,  $c_2$ , and T. These functions are expressed by the following formulas:

$$\Phi_{\varphi 1} = -\frac{R_1}{\rho_1}, \qquad \Phi_{\varphi 2} = -\frac{R_2}{\rho_2}, \qquad \Phi_{\varphi 3} = \frac{\alpha_c R_1}{\rho_3} - \frac{M_C}{M_1} \frac{R_3}{\rho_3}, \tag{6}$$

$$\Phi_{c1} = \frac{1}{\rho_5} \left( R_{51} - c_1 Q - \frac{\alpha}{c_{p5} \Delta h} (c_1 - c_{1\infty}) \right), \tag{7}$$

$$\Phi_{c2} = \frac{1}{\rho_5} \left( R_{52} - c_2 Q - \frac{\alpha}{c_{p5} \Delta h} (c_2 - c_{2\infty}) \right), \tag{8}$$

$$\Phi_T = \frac{q_5 R_5 - q_2 R_2 + q_3 R_3 - \frac{\alpha}{\Delta h} (T - T_\infty) - 4\kappa_R \sigma T^4}{\rho_5 c_{p5} + \sum_{j=1}^4 \rho_j \varphi_j c_{pj}}.$$
(9)

To complete the system of equations it is necessary to write down the dependences describing the speeds (mass rates) of physicochemical reactions. 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 forest fuel (drying), and condensed pyrolysis products burning;  $R_{51}$ ,  $R_{52}$ ,  $R_5$  are mass rates

of oxygen disappearance, combustible gases generation, and combustible gases burning accordingly:

$$R_1 = k_1 \rho_1 \varphi_1 \exp(-\frac{E_1}{RT}), \qquad R_2 = k_2 T^{1/2} \rho_2 \varphi_2 \exp(-\frac{E_2}{RT}), \tag{10}$$

$$R_3 = k_3 s_\sigma \varphi_3 \rho_5 c_1 \exp(-\frac{E_3}{RT}),\tag{11}$$

$$R_{51} = -R_3 - \frac{R_5 M_1}{2M_2}, \qquad R_{52} = (1 - \alpha_c)\nu_G R_1 - R_5, \tag{12}$$

$$R_5 = \rho_5 \min(c_2, \frac{M_2}{2M_1} c_1) k_{CO} \exp(-\frac{E_{CO}}{RT}).$$
(13)

$$Q = (1 - \alpha_c)R_1 + R_2 + \frac{M_C}{M_1}R_3.$$
 (14)

The variables and their measurement units are listed in Appendix.

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 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 (Kuznetsov et al., 2020).

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  $T_{\infty} = 304$  K, the parameters of the layer of combustible vegetation: height  $\Delta h = 0.1$  m, bulk density  $\rho_0 = 5$  kg/m<sup>3</sup>, moisture content W = 10%, coke number  $\alpha_c = 0.1$ ; in the description of turbulent processes in the gas phase:  $D_T = 1.5 \text{ m}^2/\text{s}$ ,  $\lambda_T = 1000 \text{ J/(m·s·K)}$ ; energy and mass transfer coefficients  $\kappa_R = 1.5 \text{ m}^{-1}$ ,  $\alpha = 100 \text{ W/(m^2·K)}$ . 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 (Barovik and Taranchuk, 2010).

### **3** A 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 step is  $\Delta x = \Delta y = 0.05$  metres. During the calculations the time step  $\Delta t$  was automatically determined by the stability conditions (Barovik et al., 2013), taking into account the peculiarities and intensity of physicochemical processes at each time layer (Brger et al., 2020). Actual values of  $\Delta t$ were from 0.0002 to 0.0004 seconds. 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 the intelligent processing of the results. Computer algebra system Wolfram Mathematica is used as the basis of a software platform (Barovik and Taranchuk, 2010; Orlov and Chichurin, 2020).

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 stream plots (Yankovich et al., 2019).

Another approach to investigation of the system of PDEs (1)–(5) is presented in the article (Zhiri et al., 2020). The authors of the article try to find an approximate analytical solution "using direct integration and eigenfunction expansion technique" in Maple software.

Below we present and discuss the results of calculations of how the distributions of the main characteristics of fire are being changed over time in an area of forest of a quadratic shape with a side of 20 metres. 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). The figures below show the volume density of forest fuel; green colour shows areas where the forest is in its initial state, brown colour shows areas with no combustible material (fuelbreaks or already burned forest). Also, the position and shape of the temperature of the current combustion front are synthesised in the same figures using gradient colours as a distribution density map. The vectors show the stream plots of the oxygen mass concentration.

## 4 The results of calculations how fire front overcomes 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 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 square metres, the medium size is 4.5 square metres (twice as large), and large is 18 square metres, i.e., four times the area of the middle glade.

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. 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



Fig. 1. Circular fuelbreaks. Sizes are 2.25, 4.5, and 18 m<sup>2</sup>.



Fig. 2. Fire spreading in case of three fuelbreaks  $2.25 \text{ m}^2$  each.



Fig. 3. Fire spread in case of three fuelbreaks  $4.5 \text{ m}^2$  each.



Fig. 4. Fire spread in case of three fuelbreaks  $18 \text{ m}^2$  each.

front. There is an evident difference in the front configurations after overcoming fields of different sizes. The results shown in Fig. 4 at time 195 show that the "upper front" began to move upward and to the direction opposite to the wind direction.

In Figures 2–4 vectors visualise stream plots that illustrate current flow directions for oxygen concentrations. Note that only the directions are significant, the relative lengths of the vectors do not indicate the magnitude of the rate of change in concentration. The vectors are shown only in the fire zone, in areas not affected by the fire, the values of the simulated gas concentrations and temperatures are constant, the gradient is zero.

Note the features of the results illustrated in Figures 2 and 3. At times 140 and 195 in Fig. 2 "middle" streamline runs from right to left through the centre of the "left" fuelbreak. However, in Fig. 3 (when the size of each fuelbreak increased), the corresponding "middle" streamline passes "below" the centre of the glade. This effect can be interpreted by the fact that there is no glade at the bottom (contrary to the top) and the process of combustion (disappearance of oxygen) in above and below areas does not occur symmetrically.

Let's point out a general pattern. Because combustion (increase in temperature) is a process inextricably linked with a decrease in oxygen concentration, then near the combustion fronts (Frangieh et al., 2020), oxygen stream plots are collinear with the directions of movement of the edges of the fire.

# 5 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 (Fig. 5) of the glades (Barovik and Taranchuk, 2020) 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 figures also coincide. The calculations were carried out at an equilibrium wind speed at the middle of the flame height V = 1.5 m/s.

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 of whether these differences will grow in time, or whether the fronts will take the same configuration, requires a separate study.

Let us note the differences in the dynamics of the fire, which are noticeable when analysing the stream plots. At the time 140, in the case of square and circle fuelbreaks, the stream plots are directed from right to left. However, for rectangular fuelbreaks, this direction is not observed in the evolution of oxygen concentration. Apparently, this is because the left front of the fire is "more closed" in comparison with the cases considered.



Fig. 5. Variants of fuelbreaks shapes at the moment of fire ignition.



Fig. 6. Fire dynamics for rectangular fuelbreaks geometry.



Fig. 7. Fire dynamics for quadratic fuelbreaks geometry.



Fig. 8. Fire dynamics for circular fuelbreaks geometry.

### 6 Taking into account the influence of wind speed

The influence of the wind speed on the nature of the forest fire spread is illustrated in Figures 9, 10, and 11. In the given computational experiments, in terms of geometry, the case of circular fuelbreaks of "small" size is considered. Fig. 10 (the same as Fig. 2) shows the calculation for the wind speed V = 1.5 m/s; Figures 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 metres per second, respectively. Fig. 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 convective transport due to wind force.

### 7 Discussion and future research

The results presented illustrate the dynamics of the distributions of temperatures and bulk density of combustible forest materials (the two most representative) characteristics of the processes. In general, the developed computer model calculates the distributions of six variables, which make it possible to estimate, in particular: the amount of released water vapour, the formation of polluting gases, coal, and ash.

It should be noted that due to the complexity of the calculations, the use of this computer model in real-time is impossible. At the same time, since all the results obtained in computational experiments are recorded into the database, the collections of typical process scenarios are automatically filled with the appropriate means of the software complex. Intelligent data processing is possible (Taranchuk, 2020), including the creation of electronic catalogues, the introduction of identifiers-classifiers of scenarios for calculating the development of fires in terms of attribution to typical territories and climatic conditions. The corresponding catalogues of representative scenarios can be used in conjunction with semi-empirical models (Pavlova et al., 2021; Volokitina et al., 2021).

The main direction of the software package improvement will be the addition of tools with clustering and neural network functions, their application in the preprocessing of initial distributions data, and interpretation of calculation results. Special attention will be paid to recommendations and presentation of options for using artificial intelligence tools (Wu et al., 2022) for the following tasks: 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; c) an independent task is to configure data clustering algorithms when the system receives satellite or aerial images as input data, and at the output classifies all areas of the forest, classifying them into the necessary categories (density of forest fuel material, or its absence, moisture content, height of the forest canopy and other characteristics).



Fig. 9. Wildfire overcomes circular fuelbreaks at 1 m/s wind velocity.



Fig. 10. Wildfire overcomes fuelbreaks at 1.5 m/s wind velocity.



Fig. 11. Wildfire overcomes fuelbreaks at 2 m/s wind velocity.

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### Conclusion

Using computer modelling tools, we estimated the influence of each of the following factors on the speed and direction of fire propagation:

- the presence or absence of fuelbreaks in the fire path;
- several shapes of fuelbreaks;
- the area of the fuelbreaks;
- wind velocities and direction.

The lines of oxygen concentration gradients in forest fire regions are calculated and visualised. The detected features of their configuration near the fuelbreaks are discussed.

Many computational experiments have been carried out, and the database with forest fires modelling results has been accumulated. The future research directions including the use of neural network tools are outlined.

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# **Appendix.** Nomenclature

Variables calculated in the model

variable units description						
T	K	temperature				
$\varphi_j$		volume fractions of forest fuel components $(j = 1, 2, 3, 4)$				
$\varphi_1$		dry solid fuel volume fraction				
$\varphi_2$		vegetation water volume fraction				
$arphi_3$		condensed pyrolysis product volume fraction				
$\varphi_4$		ash volume fraction				
$c_{\nu}$		relative mass concentrations of a gaseous phase components ( $\nu$ =				
		1, 2, 3)				
$c_1$		relative mass concentration of oxygen				
$c_2$		relative mass concentration of combustible gases				
$c_3$		relative mass concentration of non-combustible gases				

### Other letters and symbols

variable	units	description
V	$m \cdot s^{-1}$	equilibrium wind speed
$ ho_5$	$kg \cdot m^{-3}$	density of a gas phase (a mix of gases)
$ ho_j$	$kg \cdot m^{-3}$	true (particle) density of $\varphi_j$ component ( $j = 1, 2, 3, 4$ )
$ ho_{\infty}$	$kg \cdot m^{-3}$	unperturbed density of a mix of gases (air density)
$D_T$	$m^2 \cdot s^{-1}$	diffusion coefficient
$\lambda_T$	$J{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}K^{-1}$	turbulent thermal conductivity
$c_{p5}$	$J \cdot kg^{-1} \cdot K^{-1}$	specific heat capacity of a gas phase
$c_{pj}$	$J \cdot kg^{-1} \cdot K^{-1}$	specific heat capacity of $\varphi_j$ component $(j = 1, 2, 3, 4)$
$M_{\nu}$		molecular mass of gas phase components ( $\nu = 1, 2, 3$ )
$M_{\infty}$		molecular mass of air
$M_C$		molecular mass of condensed pyrolysis product
$\Delta h$	m	height of forest fuel layer
$\alpha$	$W \cdot m^{-2} \cdot K^{-1}$	heat exchange between atmosphere and forest fuel layer
$c_{1\infty}$		relative mass concentration of oxygen in unperturbed atmo-
		sphere
$c_{2\infty}$		relative mass concentration of combustible gases in unper-
		turbed atmosphere

variable	units	description
$T_{\infty}$	K	unperturbed ambient temperature
$q_2$	J·kg	heat effect of evaporation
$q_3$	J·kg	heat effect of charcoal burning
$q_5$	J·kg	heat effect of gaseous combustible pyrolysis products burning
$\kappa_R$	$m^{-1}$	integral (absorption and scattering) attenuation coefficient
$\sigma$	$W \cdot m^{-2} \cdot K^{-4}$	Stefan-Boltzmann constant
$k_{j}$	$s^{-1}$	pre-exponential (frequency) factor of reaction $R_j$ $(j = 1, 2, 3)$
$k_{CO}$	$s^{-1}$	pre-exponential factor of reaction $R_5$
$E_j$	$J \cdot mol^{-1}$	energy activation of reaction $R_j$ $(j = 1, 2, 3)$
$E_{CO}$	$J \cdot mol^{-1}$	energy activation of combustible gaseous pyrolysis products
		burning
R	$J \cdot K^{-1} \cdot mol^{-1}$	universal gas constant
$s_{\sigma}$	$\mathrm{m}^{-1}$	condensed pyrolysis product surface area to volume ratio
$\nu_G$		proportion of gaseous combustible pyrolysis products

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