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Mathematical Simulation of Forest Fuel Pyrolysis and Crown Forest Fire Impact for Forest Fire Danger and Risk Assessment

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Abstract: In order to predict and assess the danger from crown forest fires, it is necessary to study the thermal degradation of different forest fuels in a high-temperature environment. In this paper, the main characteristics of pyrolysis accompanied by moisture evaporation in a foliage sample of angiosperms (birch) were investigated within conditions typical for a crown forest fire. The heat and mass transfer in the forest fuel element is described by the system of non-stationary non-linear heat conduction equations with corresponding initial and boundary conditions. The considered problem is solved within the framework of the three-dimensional statement by the finite difference method. The locally one-dimensional method was used to solve three-dimensional equations for heat conduction. The simple iteration method was applied to solve nonlinear effects caused by the forest fuel pyrolysis and moisture evaporation. The fourth kind of boundary conditions are applicable at the interface between the sub-areas. Software implementation of the mathematical model is performed in the high-level programming language Delphi in the RAD Studio software. The characteristic changes in the sample temperature field and the phase composition under high-temperature exposure from a forest fire are presented. The induction period of the thermal decomposition of dry organic matter in the sample was determined. Recommendations are made about key features of accounting for the pyrolysis and evaporation processes when predicting forest fire danger. The research results can be used in the development and improvement of systems for predicting forest fire danger and environmental consequences of the forest fires.

Keywords: forest fuel; heat and mass transfer; pyrolysis; three-dimensional statement; birch leaf; mathematical modeling; induction period; forest fire danger

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1. Introduction

Forest fires have become commonplace for many countries with large forests, such as Russia, USA, Canada, Portugal, France, Greece, Turkey, Australia, Tunisia, Argentina, and Brazil [1–8]. The main factors causing a forest fire include climatic conditions (high air temperature, periods with no precipitation, strong winds, low humidity), anthropogenic load (from urbanization, agricultural activities, proximity of megacities, highways, railways, industrial enterprises to forest plantations), and thunderstorm activity [9].

Damage from forest fires affects many aspects of life in nature and humans. For example, fires contribute to a decrease in the number of organisms in an ecosystem, an increase in the probability of disease and attack by bacteria and insects. Forest fires greatly affect the soils by erosion and destruction their properties. Moreover, fires lead to vegetation alteration, regeneration inhibition as well as an increased risk of disease and epidemics [10]. Fires also entail deaths and direct financial costs to rebuild infrastructure. Loss reports from forest fires for the period from 1987 to 2014 estimate an average damage of up to USD12.3 million without taking into account the costs of extinguishing the fires and rehabilitation of victims [11].

This study is tied to the territory of the Russian Federation, but the results in reality may be relevant to other boreal countries. This is due to the fact that birch is the predominant hardwood species in many forested regions of these countries. Secondly, birch is a typical deciduous species, on the example of which policies may be considered for other deciduous trees. It is clear that in deciduous forests, forest fires have a low ignition probability and subsequently less risk of spread of a surface forest fire, compared to other types of forest. This fact is beyond doubt. However, a significant part of the forest areas are mixed stands with the inclusion of deciduous species, especially birch. In such stands, it is necessary to take into account the presence of inclusions of deciduous trees. Numerous experiments on the ignition of hardwood litter (birch leaf), conducted at Tomsk Polytechnic University, showed that even last year's partially decomposed birch leaves, when a heated metal or non-metal particle falls on them, have a lower ignition temperature, all other things being equal, compared to coniferous trees. That is, in the ground forest fuel layer mainly composed, for example, of the needles of pine, spruce or cedar, there may be local inclusions of birch leaves, which can ignite at lower temperatures. The process of spreading the flame will then switch to coniferous forest fuel elements, which will already to the initiation and spread of a surface forest fire. As a result, the fire danger of a number of mixed forests, especially those with a small inclusion of deciduous species, may be higher than the fire danger of pure coniferous stands. A similar effect can occur when the crown forest fire front spreads over a forest stand of coniferous trees with the inclusion of deciduous species. All these issues require detailed study, and this article to some extent creates the foundation for future similar studies in the case of the boreal forest zone.

Prediction methods are key to basis of effective technology for forest fire prevention. Accurate and high-quality prediction of fire occurrence and spread requires knowledge about forest fuel behavior in a high-temperature environment. The purpose of this work is mathematical modeling of heat and mass transfer processes in a forest fuel element (birch leaf) exposed to a high-temperature environment. The moisture evaporation and thermal decomposition of dry organic matter are taken into account. The main objectives of the research are: (1) Formulation of a mathematical model; (2) Selection and adaptation of the numerical method; (3) Numerical implementation of the mathematical model; (4) Analysis of theoretical implications; (5) Development of recommendations for the practical application of the mathematical model.

2. Background

Combustion refers to the exothermic reaction between the fuel and the oxidizing agent (usually atmospheric oxygen) accompanied by an intense energy release through heat and mass exchange processes [12,13]. The following sequence of phases can be distinguished during forest fuel combustion [14]: inert heating, moisture evaporation, pyrolysis, flame combustion, carbonization and afterburning of coke.

The processes occurring immediately before the forest fuel ignition need to be studied in detail. Forest fuel drying is one of the most important and less studied stages of the combustion process in terms of environmental conditions. Drying is understood as water evaporation from the material. Therefore, it is necessary to distinguish the concepts of free and bound water [15]. Water is considered free when the values of the saturated vapor pressures are equal. Bound water suggests stronger bonds with the material. It should be remembered that, the partial pressure of bound water is less than for free water at the same temperature. The evaporation of bound water is quite energy-consuming and includes many stages [15]. It is generally accepted that there are three types of bonding between the water and material, based on the amount of work required to remove one mole of moisture: chemical, physicochemical, and physicomechanical. Chemically bound water has the highest binding energy and is not removed during drying. Physicomechanically bound water requires the least energy for removal [15].

When studying forest fuel drying, the main tasks are to determine the mechanism itself and the process time, as well as the fuel thermokinetic parameters and moisture

content. Usually numerical and experimental methods are used to describe the drying process under various boundary conditions.

Many research works are aimed at determining the forest fuel moisture content (FMC). FMC is usually described as the ratio between the mass of water and the mass of dry organic matter. This metric is key to fuel performance and fire potential. First, a high moisture content contributes to a delay in fuel ignition and combustion, since there is a need to evaporate the water first. Secondly, the high moisture content also leads to an increase in thermal conductivity and heat capacity. Thirdly, water vapor reduces the ignition potential and combustion temperature, and dilutes oxygen [16].

The forest fuel moisture content is determined by its essential features, such as hygroscopicity, cellular structure and thermophysical properties. All these features will be different for living and dead fuels. The water evaporation process from dead fuel is due to the evaporation processes from the cell walls, the vapor diffusion through the cells voids and further condensation on the cell walls. The difference in the atmospheric pressure and water vapor pressure in forest fuel characterizes the moisture content dynamics [16]. The liquid movement process in live fuel is due to osmosis and across cell voids, moving by diffusion and capillary forces. The diffused water is then drawn to the foliage through the conductive xylem tissue in the wood by tensile pressure caused by the water potential, which is controlled by the vapor pressure gradient from the air to the plant [16]. The thermogravimetric method is often used to determine the FMC values. The forest fuel samples are dried in an oven for the certain period of time. Then the samples' weights before and after drying are compared. It is need to be mentioned that maintaining relatively low temperatures (80–85 °C) for long periods of time (up to 72 h) gives more accurate results [16].

Various studies have been published in the literature devoted to determining the FMC and describing its influence on the drying and ignition processes [17,18]. It was noted that the moisture loss is rather rapid at the initial stage, and then the process stabilizes to an exponential decay [17]. The results of the analysis in [18] found that the conversion factor between the relative air humidity and the FMC in case of forest litter could not be established because the input data were very different [18]. There are researches devoted to the determination of leaf or forest litter moisture using radiative transfer models (RTM) [19–22]. Therefore, it possible to obtain the necessary data for mapping forest areas and more accurate prediction of forest fire danger. In addition to determining the FMC, many scientists are engaged in a mathematical description of this process [23–25]. These models allow analysis of environmental parameters, such as ambient temperature, average wind speed, solar radiation, different heat exchange mechanisms with the surface area of the atmosphere, and relative humidity, to enable fire danger risk prediction.

Data on the drying process can also be used to formulate criteria for assessing the probability of forest fires. For example, the Nesterov empirical drought index, which describes five levels of potential fire danger risk, is used in Russia [26]. This index is based on a mathematical model using a weighted difference between temperature and dew point. Daily synoptic data (temperature, humidity, and daily precipitation) is used as input data for this index [26,27].

The Keetch–Byram drought index (KBDI) is used in Europe to estimate the risk of potential fires. This approach calculates the amount of water from rainfall that is necessary to replenish soil in a field. Daily weather observations (maximum air temperature, rainfall) are used for the calculations [28]. The Angstrom index is used in the Scandinavian peninsula for prediction of the number of fires on any given day. It is considered as one of the simplest drought indices based on the values of air temperature and relative humidity [29]. The Canadian Forest Fire Weather Index (FWI) system, which consists of six components calculated from meteorological data, can also be mentioned here. The first three components describe the moisture content of forest fuel of different sizes [30]. Today, research is being actively carried out aimed at choosing the optimal criteria for use in predicting systems for forest fire danger for a specific area [31–33]. Thus, the main empirical drought indices were

tested in the conditions of the European Mediterranean by the correlation with real data on fuel moisture [33]. The final statistical analysis of the collected data showed that the KBDI is the most appropriate one for the considered conditions.

Modeling heat and mass transfer processes requires considering the process of forest fuel pyrolysis. This process is accompanied with the release of volatile compounds. These products support further ignition and combustion. Pyrolysis is a biomass transformation of a mixture of oxygen-containing organic compounds at high temperatures and in an inert atmosphere irequires [34,35]. Pyrolysis comprises a set of primary and secondary reactions. During these reactions biomass polymers' structure is destroyed and transformed and volatile compounds are released [36].

When modeling the pyrolysis process, it is necessary to allow for biomass composition and the reactions between the components. There are three group of models considering this process on different levels (mechanistic, network and kinetic models) [37].

Kinetic models are used to describe forest fuel pyrolysis in general. These models do not need extensive structural data. Adequate results can be obtained within the experimentally determined kinetic parameters. These models are quite popular because of their simplicity and ability to discern the main patterns of the process, as well as good agreement with experimental data. However, they do not model biomass structural changes and released volatiles adequately [37].

Kinetic models refer to different types of reactions occurring during decomposition. These models fall into two categories depending on the reaction mechanism: lumped and distributed models. Lumped models assume that biomass components and reaction products are combined into three product classes (tar, gas and char). It is suggested that biomass is converted to these three products through one-step or multi-step reactions without taking into account the reaction pathways [38,39]. In the case of distributed models, the pyrolysis products are formed via an infinite number of independent parallel reactions with different activation energies. These models enable accurate estimation of the mass loss over the entire conversion process. The methods used to calculate kinetic parameters for such models are divided into two types: distribution-free methods and distribution-fitting methods [38,39].

When using kinetic models, the question of the number of reactions and their sequence is considered. The modeling of processes using various approaches is discussed in [40]. A one-component mechanism of primary pyrolysis assumes that gas, tar and char are formed from the biomass with different reaction rates. A three-stage sequential pyrolysis mechanism considers the competitive formation of compounds related to either a gas or a solid phase. A secondary reaction model is also described. It was noted that various types of secondary reactions become active under the conditions of high temperatures and long exposure time. In summary, the one-component mechanism of biomass pyrolysis uses experimental data obtained under isothermal or rapid heating conditions. The model of three parallel reactions is also popular in the literature. According to this model, biomass decomposition occurs by decomposition of its main components without any interactions. A kinetic equation can be written for each component based on the dependence of the fugitive emission at as particular moment of time on the preexponential value and activation energy [41,42].

Moreover, it is interesting to compare different options for modeling in order to choose the appropriate one for different types of fuels and heating conditions. For example, two competing models (linear and Arrhenius model) were evaluated for grass fuel pyrolysis in physical modeling of fires [43]. The linear model considered independent variables and interspecific variation. In paper [44], the three schemes of birch wood pyrolysis were assessed for their efficiency by comparing with results of thermogravimetric experiments. The one-stage first-order reaction scheme proved to be more accurate in making good heat rate predictions. A fire dynamics simulator (FDS) pyrolysis program was used to perform mathematical simulation. Such computer code can be used both as an independent solution for pyrolysis and to study the phenomenon of conjugate flame propagation. In [45], a

one-dimensional mathematical model of pyrolysis was developed based on the global kinetic model, allowing for the various thermophysical properties and radiative heat flux and arbitrary boundary conditions. However, good agreement of the results was achieved only at low heat fluxes. The model needs to be adapted for real fire conditions to improve the data consistency.

In addition, there are works describing the peculiarities of the pyrolysis process during liquid evaporation [46–48]. Such researches are necessary for the establishing the main patterns of the process occurring during pyrolysis itself as well as during and after its suppression.

This analysis of modern research shows the level of global interest in the problem of modeling the processes preceding fuel ignition. Understanding the mechanisms of these processes will contribute to improved management of forest fire danger.

3. Materials and Methods

The warty birch is known as the most common species throughout the forest and forest-steppe zone of European countries. For this reason, the foliage from this tree was used to conduct the research.

The morphological characteristics of the typical leaf were 4 cm in the longitudinal direction and 2.5 cm in the transverse (in the widest section), The leaf thickness is about 0.2 mm [49].

The solution area (a birch leaf) was represented as a three-layer plate. It was assumed that the first and third layers were composed of dry organic matter, while the second layer was a mixture of water and dry organic matter. In the simulation, heat transfer due to conduction was considered. The processes of moisture evaporation and thermal decomposition were taken into account. The temperature dependence of the fuel thermophysical parameters was neglected. Heat transfer along the x, y, z axes was investigated. The solution area is presented in Figure 1.

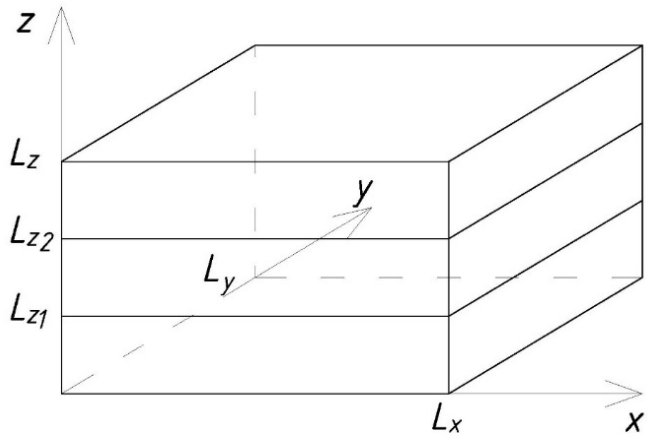


Figure 1. Geometry of the solution area.

The experimental setup described in [50] made it possible to simulate the impact of a high-temperature environment typical for various forest fires. In reality, a birch leaf has an irregular geometric shape. However, for simplicity of numerical implementation, such a typical sample can be inscribed in a rectangle. This article uses the dimensions of this particular rectangle. In some works on numerical methods, it is proposed to use geometric figures of regular geometric shape as a discrete analogue of the real object under consideration [51]. Such an approach of extending the computational domain to the boundaries of the figure, into which the real object is inscribed, is used in this article. It allows one to obtain both qualitative characteristics of the process under study and approximate quantitative characteristics.

When numerical simulation, the three-dimensional heat conduction equation, and the kinetic equation were solved:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \lambda_i \left(\frac{\partial^2 T_i}{\partial x^2} + \frac{\partial^2 T_i}{\partial y^2} + \frac{\partial^2 T_i}{\partial z^2} \right) - q_p k_1 \rho_4 \varphi_4 \exp\left(-\frac{E_1}{RT_i} \right) - q_{ev} w_{ev} \quad (1)$$

$$\rho_4 \frac{\partial \varphi_4}{\partial t} = -k_1 \rho_4 \varphi_4 \exp\left(-\frac{E_1}{RT_i} \right) \quad (2)$$

$$\rho_5 \frac{\partial \varphi_5}{\partial t} = -w_{ev} \quad (3)$$

where w_{ev} is the evaporation rate. This is calculated by the formula:

$$w_{ev} = \frac{A(P^s - P^*)}{\sqrt{\frac{2\pi RT_i}{M}}} \quad (4)$$

where A is the accommodation coefficient, P^s is the saturated vapor pressure, R = 8.31 J/(mol·K) is the universal gas constant, M is the molecular weight.

This evaporation rate equation was given in [52]. The procedure of defining values and some typical values of the biomass accommodation coefficient were presented in [53–55].

The initial conditions were written as:

$$T_i|_{t=0} = T_{i0} \quad (5)$$

$$\varphi_i|_{t=0} = \varphi_{i0} \quad (6)$$

The boundary conditions were written as follows:

$$z = 0 : -\lambda_1 \frac{\partial T_1}{\partial z} = \alpha \left(T_1 - T_{ff} \right) \quad (7)$$

$$z = L_{z_1} : -\lambda_1 \frac{\partial T_1}{\partial z} = -\lambda_2 \frac{\partial T_2}{\partial z}, T_1 = T_2 \quad (8)$$

$$z = L_{z_2} : -\lambda_2 \frac{\partial T_2}{\partial z} = -\lambda_3 \frac{\partial T_3}{\partial z}, T_2 = T_3 \quad (9)$$

$$z = L_z : -\lambda_3 \frac{\partial T_3}{\partial z} = \alpha \left(T_3 - T_{ff} \right) \quad (10)$$

$$x = 0 : -\lambda_i \frac{\partial T_i}{\partial x} = \alpha \left(T_i - T_{ff} \right) \quad (11)$$

$$x = L_x : -\lambda_i \frac{\partial T_i}{\partial x} = \alpha \left(T_i - T_{ff} \right) \quad (12)$$

$$y = 0 : -\lambda_i \frac{\partial T_i}{\partial y} = \alpha \left(T_i - T_{ff} \right) \quad (13)$$

$$y = L_y : -\lambda_i \frac{\partial T_i}{\partial y} = \alpha \left(T_i - T_{ff} \right) \quad (14)$$

$$\sum_{i=4}^{6} \varphi_i = 1 \quad (15)$$

where α is the heat transfer coefficient; α_1 is the first left running coefficient; α_j^* is the first running coefficient in the border between the leaf layers; c is the specific heat; E is the activation energy of the pyrolysis; φ_4 is the dry organic matter fraction; φ_5 is the moisture fraction; φ_6 is the gas and vapor fraction; h is the spatial step; i = 1,2,3 are the forest fuel layers; k is the pre-exponent of the pyrolysis; λ is the thermal conductivity coefficient; L_x, L_y and L_z are the dimensions of the decision area in x-direction, y-direction and z-direction,

respectively; N, L and M are the number of nodes in x-direction, y-direction and z-direction, respectively; q_p is the thermal effect of the pyrolysis reaction; Q(t,x,y,z) is the nonlinear part of the equation; R is the universal gas constant; ρ is the density; t is the time coordinate; T_{ff} is the flame temperature; T_i is the temperature of the forest fuel in the point of the i-th layer; W_{ev} is the mass rate of evaporation; x, y, z are the spatial coordinates.

Initial data:

$$\rho_1 = \rho_4, \rho_2 = \rho_4\varphi_4 + \rho_5\varphi_5, \rho_3 = \rho_4 \quad (16)$$

$$c_1 = c_4, c_2 = c_4\varphi_4 + c_5\varphi_5, c_3 = c_4 \quad (17)$$

$$\lambda_1 = \lambda_4, \lambda_2 = \lambda_4\varphi_4 + \lambda_5\varphi_5, \lambda_3 = \lambda_4 \quad (18)$$

ρ_4 = 290.0 kg/m^3; c_4 = 1450.0 J/(kg·K); λ_4 = 0.13 W/(m·K); ρ_5 = 1000.0 kg/m^3; c_5 = 4180.0 J/(kg·K); λ_5 = 0.588 W/(m·K); q_p = 1000.0 J/kg; $k_1 = 3.63 \cdot 10^4$, E_1/R = 9400 K; α = 80 W/(m^2·K); T_{ff} = 1000 K.

In 2000, Professor Grishin from Tomsk State University presented the latest version of the general mathematical model of a forest fire [56]. This spatial mathematical model of a forest fire considers movement, heat and mass transfer, physicochemical processes in the forest fire front, as well as the convective column formation over the forest fire center. This complex mathematical model has never been fully implemented numerically; significant computing resources of multiprocessor computing systems with parallel data processing are required [57]. When solving problems using the forest fire theory, implicit numerical methods [58–60] are used, which are difficult to parallelize. Often, such parallel implementation allows the use of large computational domains with a detailed spatial grid, but the acceleration and efficiency of such parallel programs are low [61]. Secondly, for the numerical implementation of the general mathematical model [56], a large set of different physical constants and parameters is needed. Not all of the initial data can be obtained for a specific calculation when modeling a forest fire. Frank Albini described Grishin's type of general mathematical model as a model of the future since it is not yet possible to implement it completely on computers at present. Therefore, many researchers use the approach of developing simplified or reduced mathematical models based on this general mathematical model [56]. In this research, a general mathematical model was reduced to a particular case of modeling heat and mass transfer in a forest fuel element. In addition, specific boundary conditions have been formulated that make it possible to simulate the effect of a high-temperature environment characterizing the influence of a crown forest fire front on a forest fuel sample. Other forest fires scenarios can also be used [62].

The differential equations were solved using the finite difference method [58–60]. This method involves using finite-difference approximations instead of derivatives in the differential equation. The sample under study itself is represented as a set of nodes (a special finite-difference mesh is imposed on it). By approximating (replacing) the partial derivatives of the differential equation by finite differences, a system of linear algebraic equations is obtained to determine the temperature as a local characteristic at each grid point. The resulting system is open-ended. A difference representation of the boundary conditions is used to close this system. The obtained system of linear algebraic equations is solved by numerically using a computer.

A brief description of the computational procedure may be given here (Figure 2). First, the initial data as well as the parameters (thermophysical, geometrical and thermochemical characteristics) are set. It is assumed that the leaf layers have an initial temperature equal to the air temperature. Aan exposure time and the temperature of the forest fire front can also be defined here. This stage is also used to determine spatial and temporal steps for the computational mesh using uniform discretization. The second stage entails the computational circle within exposure time consisting of two sub-circles to compute in 2 directions while another coordinate is fixed. Thus, each sub-circle is computed using a set of one-dimensional tasks of heat conductivity along chosen directions. Each one-dimensional task represents as a sequence of forward (computation of all coefficients starting from the first run-through coefficients based on left boundary conditions) and

backward (computation of temperature distribution starting from the temperature on the right border using the right boundary conditions) runs for the marching method. Then, computation of all temperature distributions on definite directions is processed. Each subcircle requires using simple iteration methods to resolve nonlinear terms of equations. After finishing the calculations, the results are saved in files. The data analysis and visualization is conducted using Origin Pro software [63].

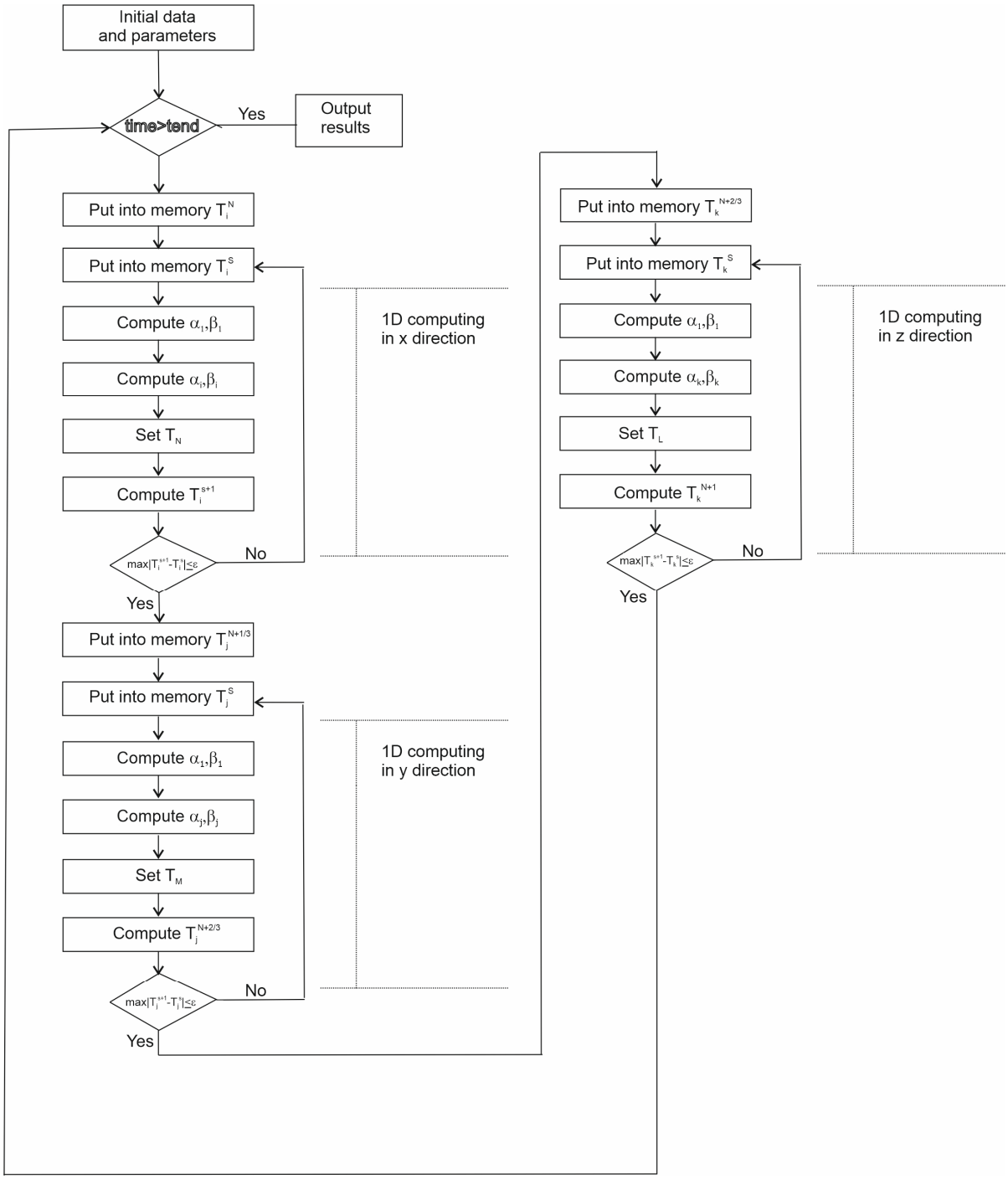
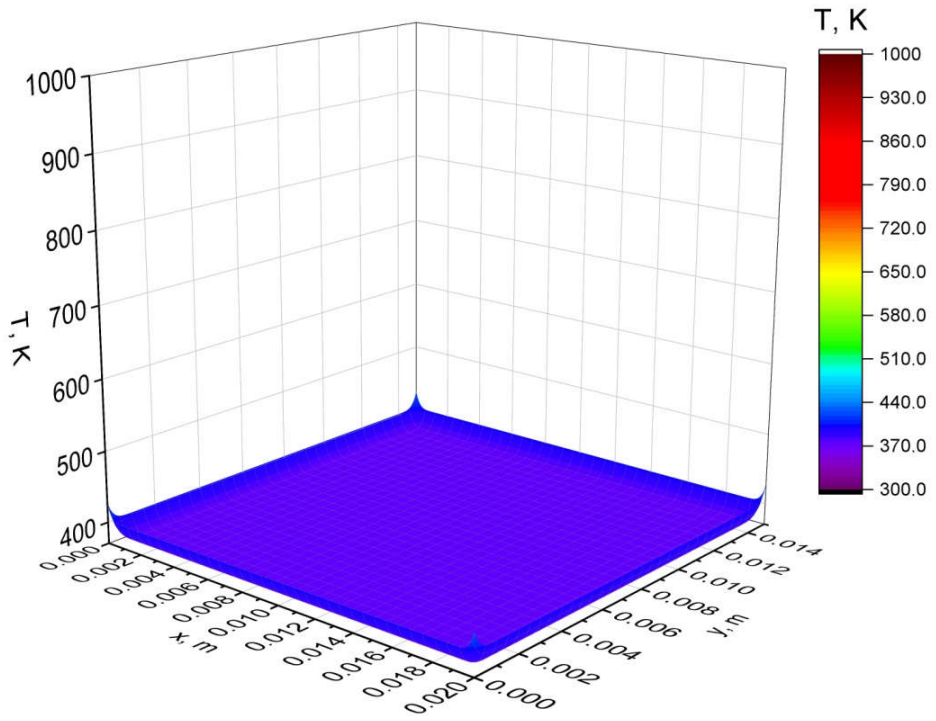


Figure 2. Computational procedure: T_i^N, T_i^{N+1}, T_i^S are the temperatures in computational node I for N temporal layer N, temporal layer N+1, and S-th and S+1-th iterations; α_i, β_i are the running coefficients; ε is the computational precision; T_N, T_M, T_L are the temperatures in the last computational node for x, y and z directions.

4. Results

A description of the simulation results should be provided. Figures 3 and 4 show typical temperature distributions in different planes of the sample at exposure times of 0.2 and 3 s. The fire temperature was equal to 1000 K.



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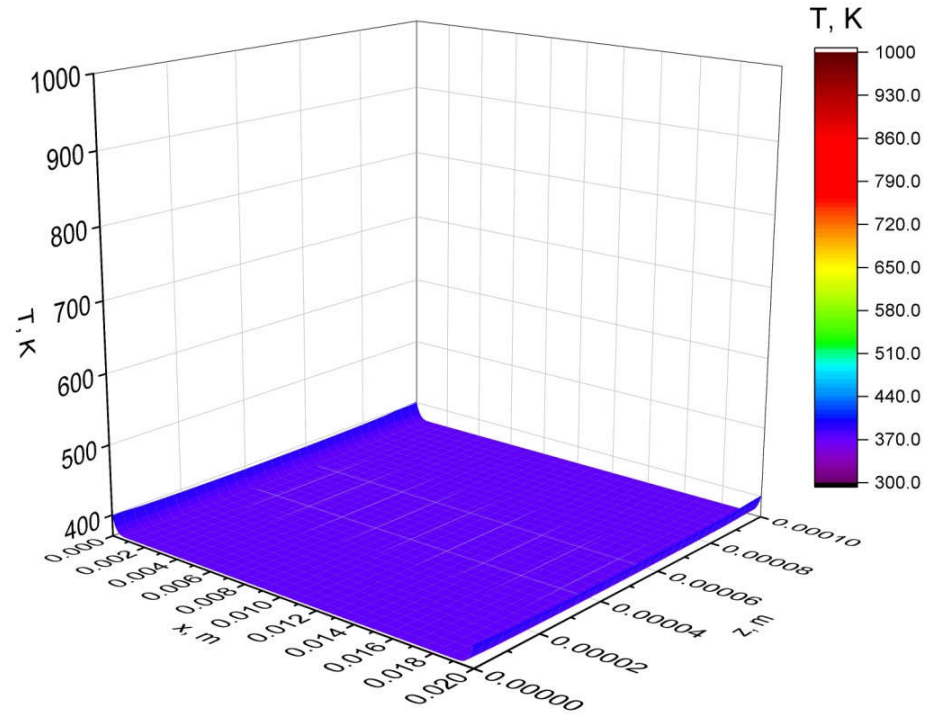
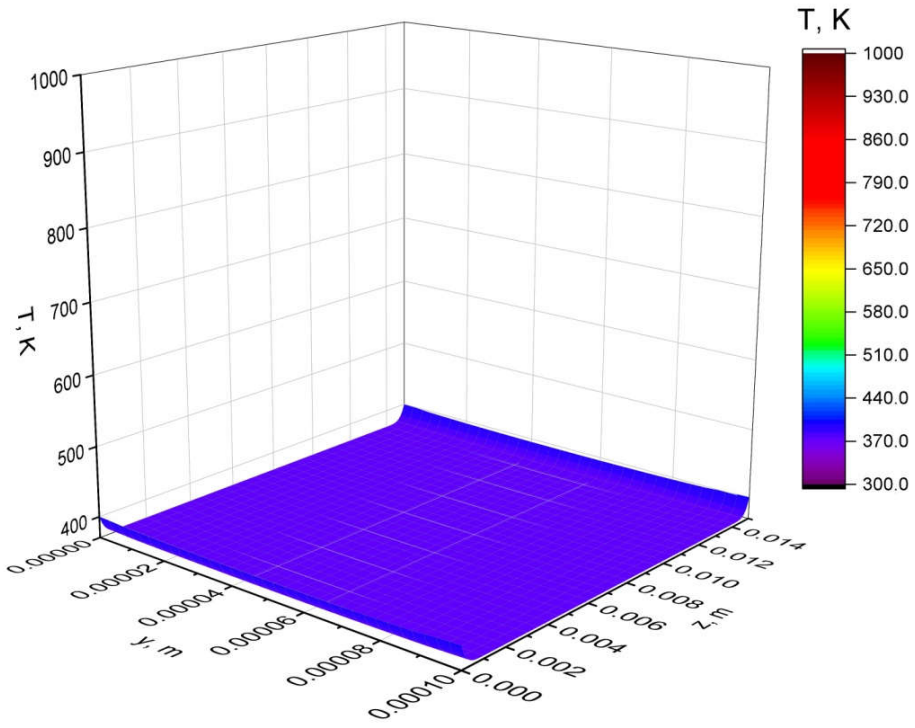


(**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. Typical temperature fields in the plane xy (**a**), xz (**b**) and yz (**c**) in a birch leaf plate (T_{ff} = 1000 K, t = 0.2 s).

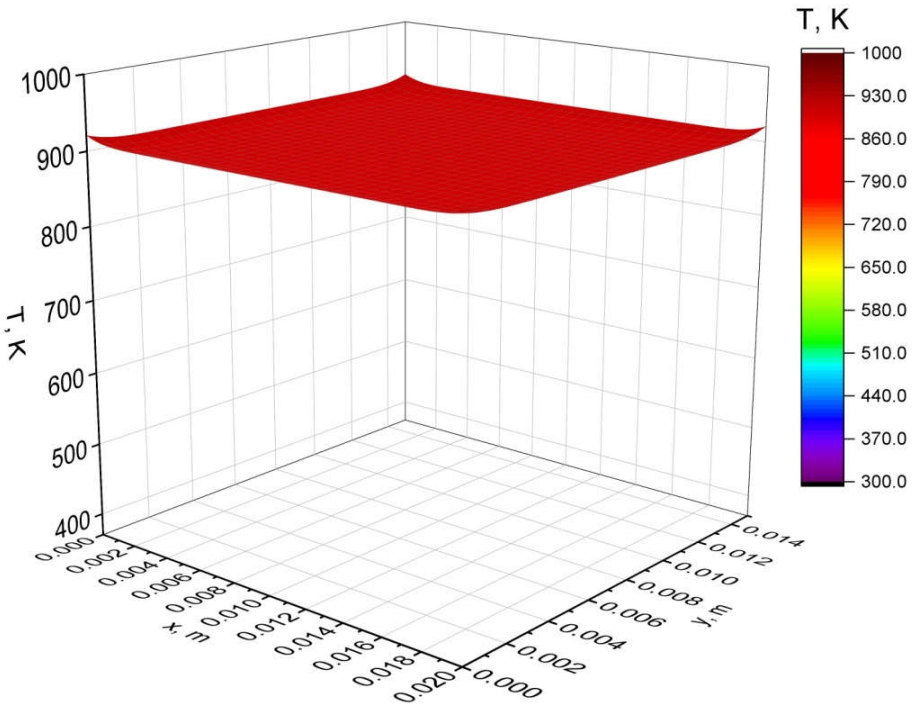


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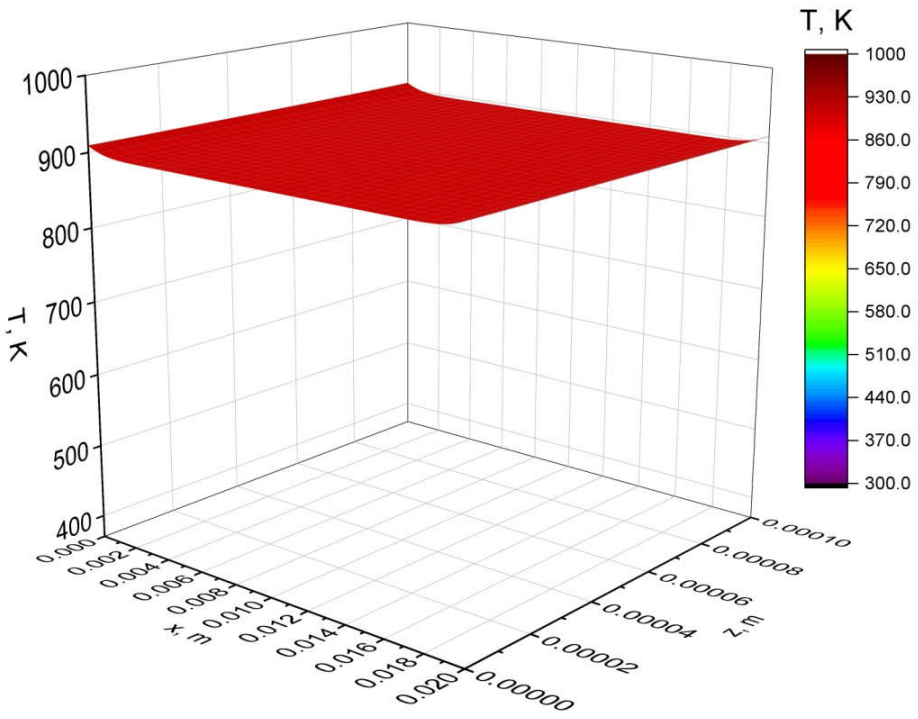
Figure 4. *Cont.*



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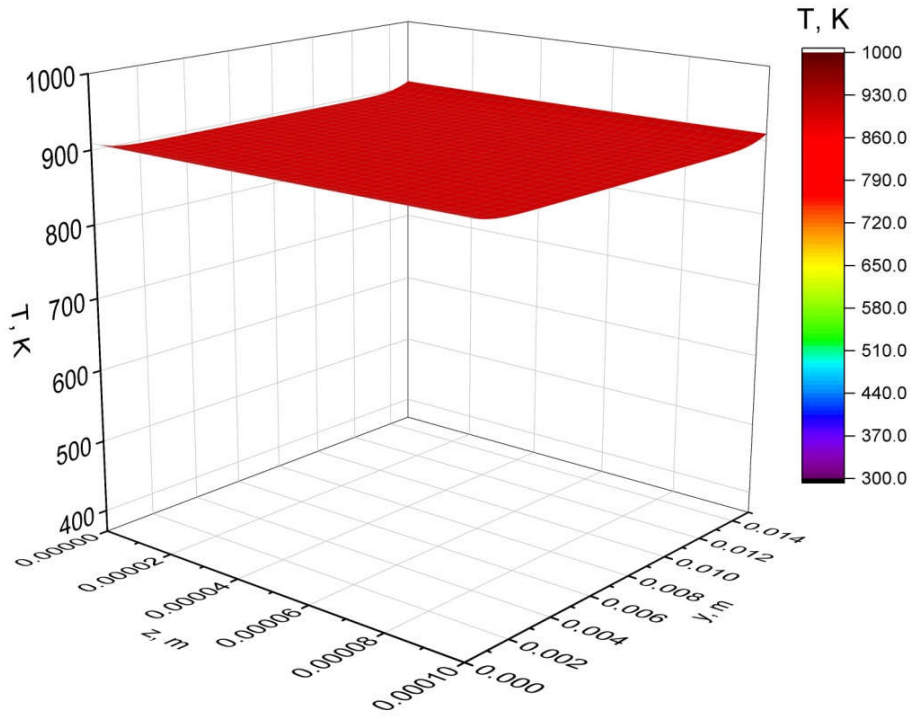
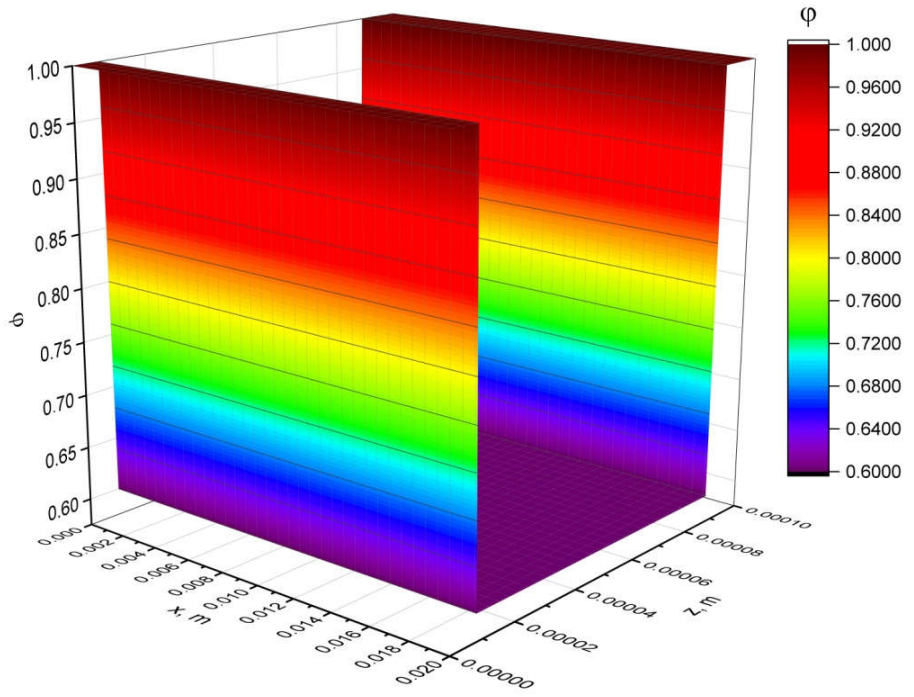


(**c**)

Figure 4. Typical temperature fields in the plane xy (**a**), xz (**b**) and yz (**c**) in a birch leaf plate (T_{ff} = 1000 K, t = 3 s).

Figures 5–7 show the distributions of the volume fractions of phases of dry organic matter, water and gaseous products in different planes of the sample at an exposure time of 0.2 s and a temperature of 1000 K.



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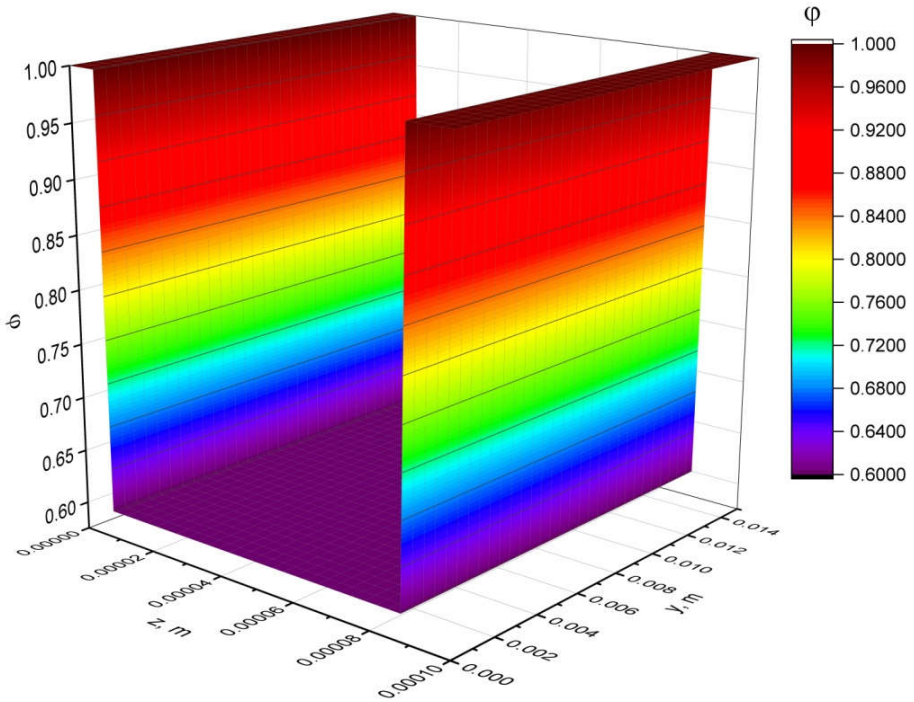
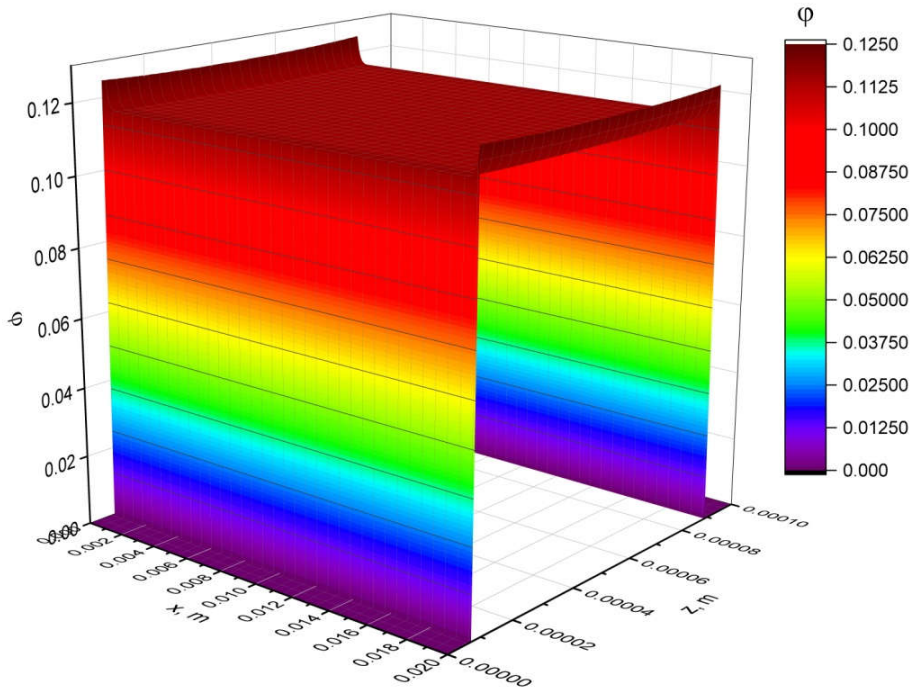


(**b**)

Figure 5. Distribution of dry organic matter in the xz (**a**) and yz (**b**) planes of a leaf plate of a birch leaf (T_{ff} = 1000 K, t = 0.2 s).



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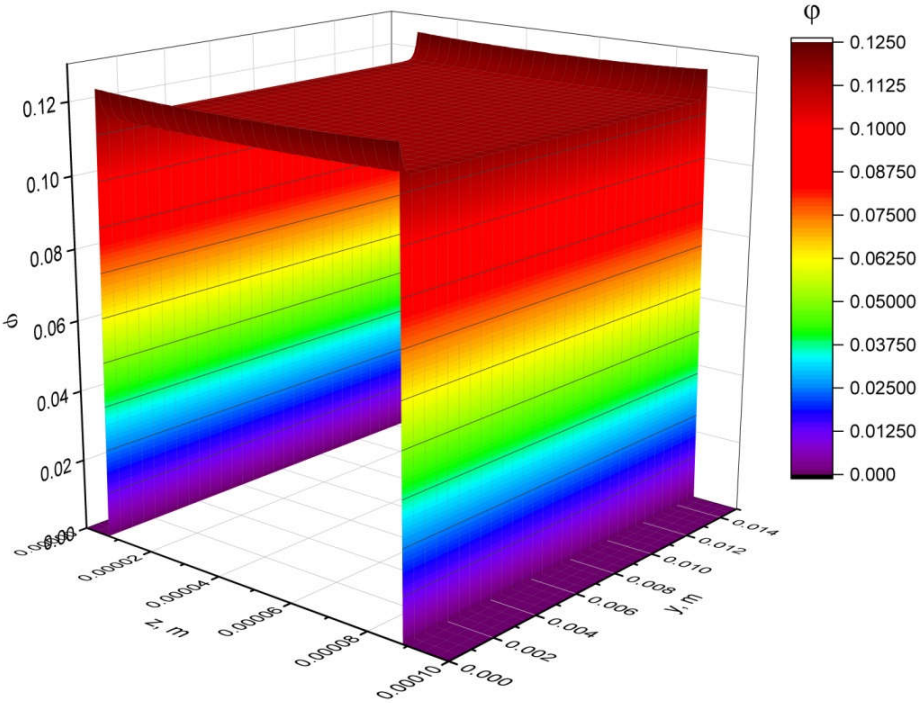
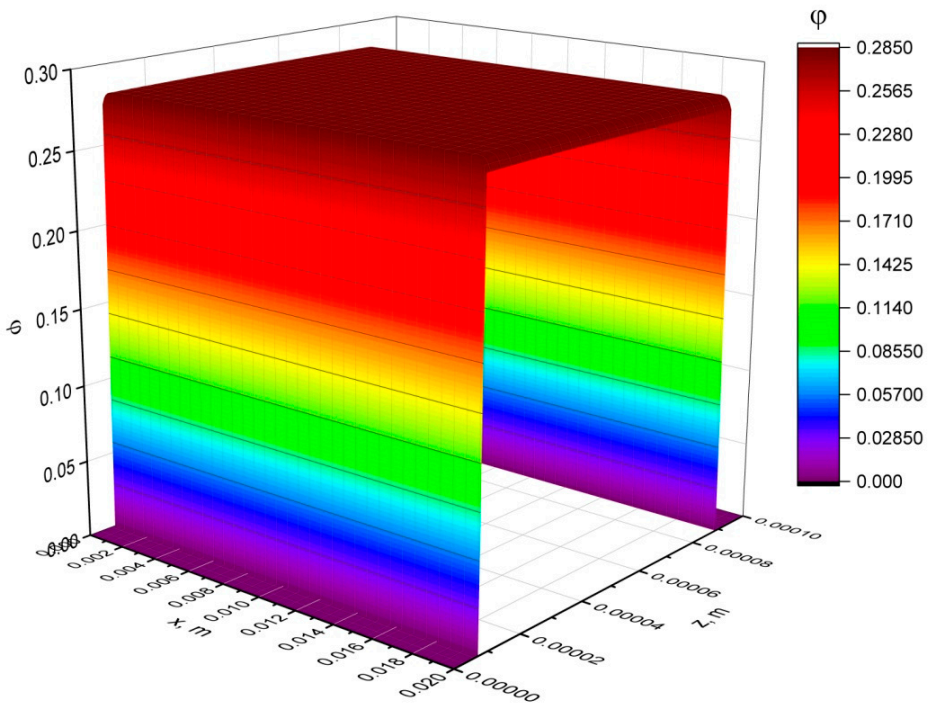
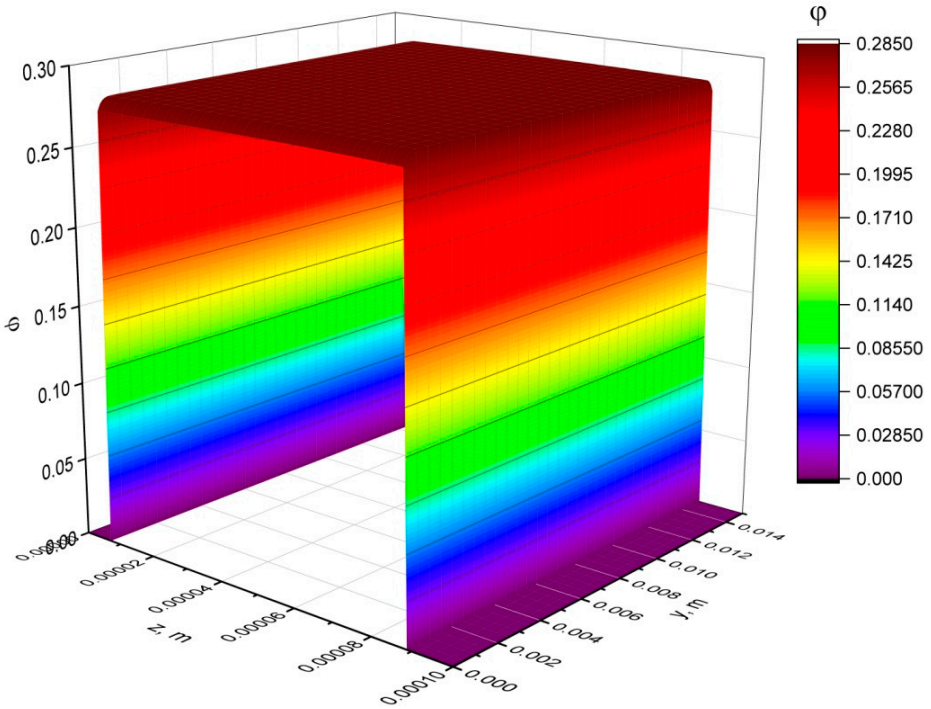


(**b**)

Figure 6. Distribution of water in the xz (**a**) and yz (**b**) plane of a birch leaf plate (T_{ff} = 1000 K, t = 0.2 s).



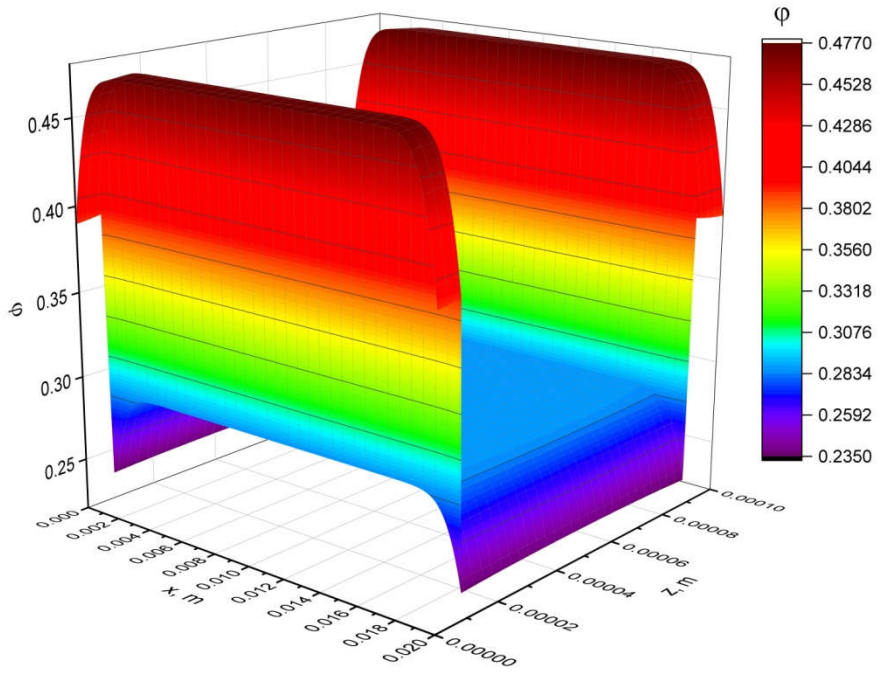
(**a**)



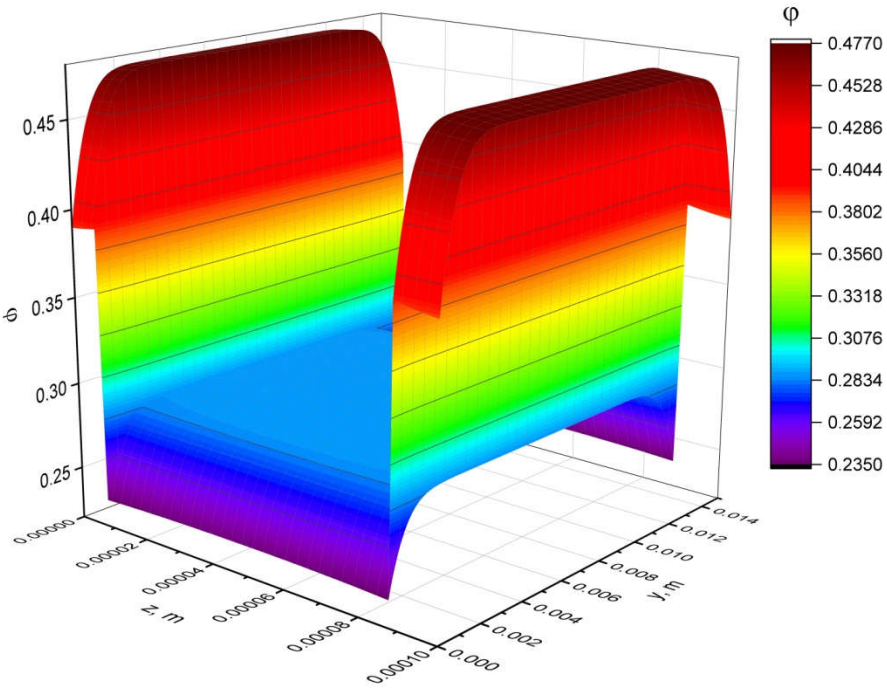
(**b**)

Figure 7. Distribution of the vapor-gas mixture in the xz (**a**) and yz (**b**) planes of a birch leaf plate (T_{ff} = 1000 K, t = 0.2 s).

Figures 8–10 show the same distributions for an exposure time of 3 s. These are typical results for a low-intensity forest fire, which can subsequently transform into crown forest fire. In addition, scenario calculations were carried out for the conditions of a low-intensity surface forest fire and a crown forest fire [64].

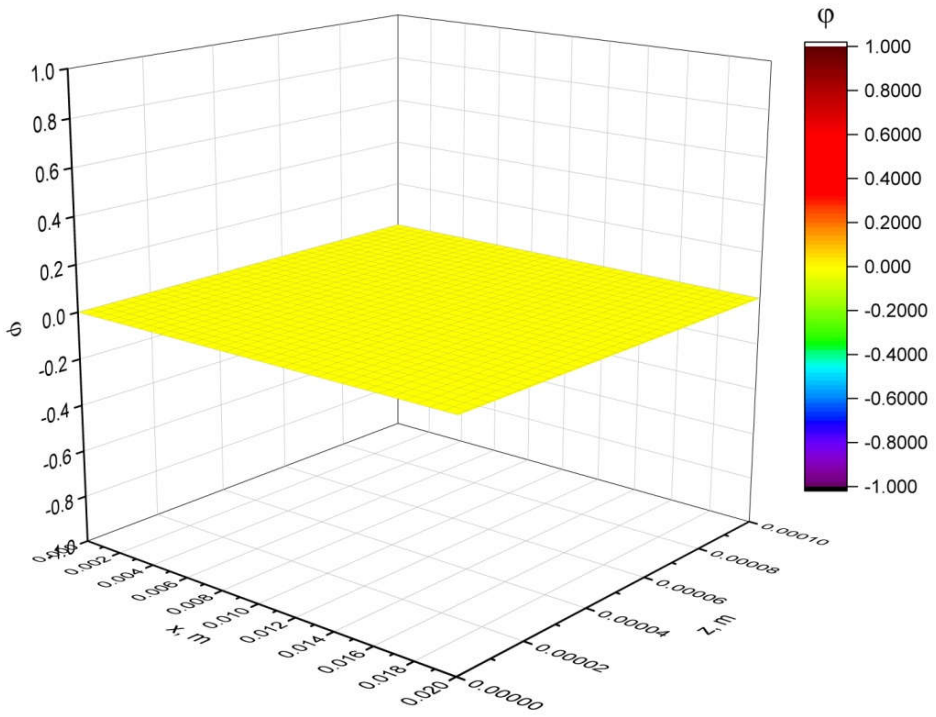


(**a**)

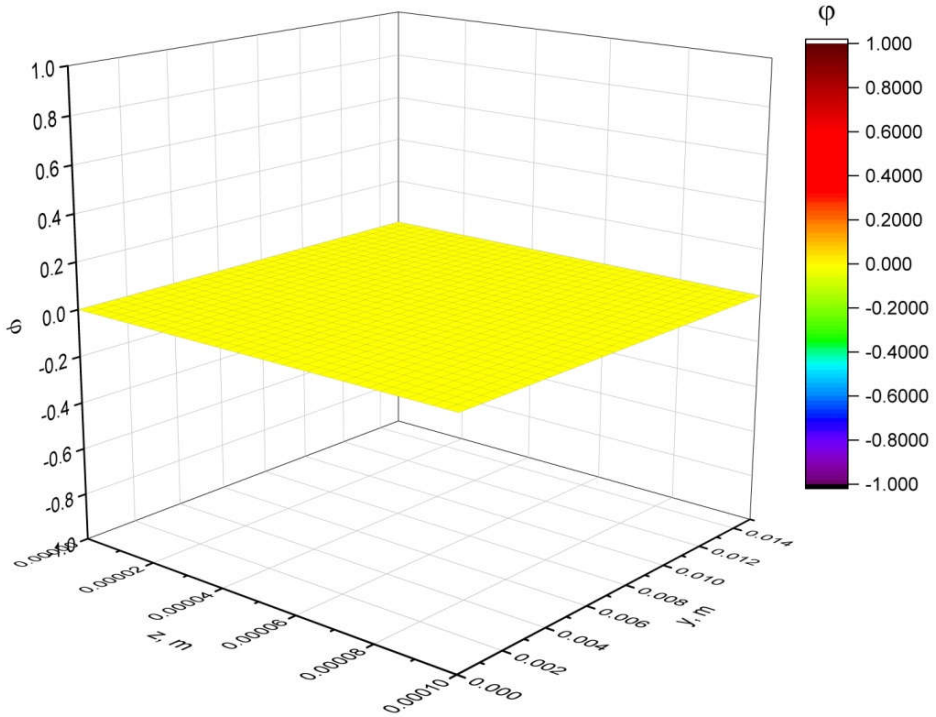


(**b**)

Figure 8. Distribution of dry organic matter in the plane xz (**a**) and yz (**b**) of a leaf plate of a birch leaf (T_{ff} = 1000 K, t = 3 s).

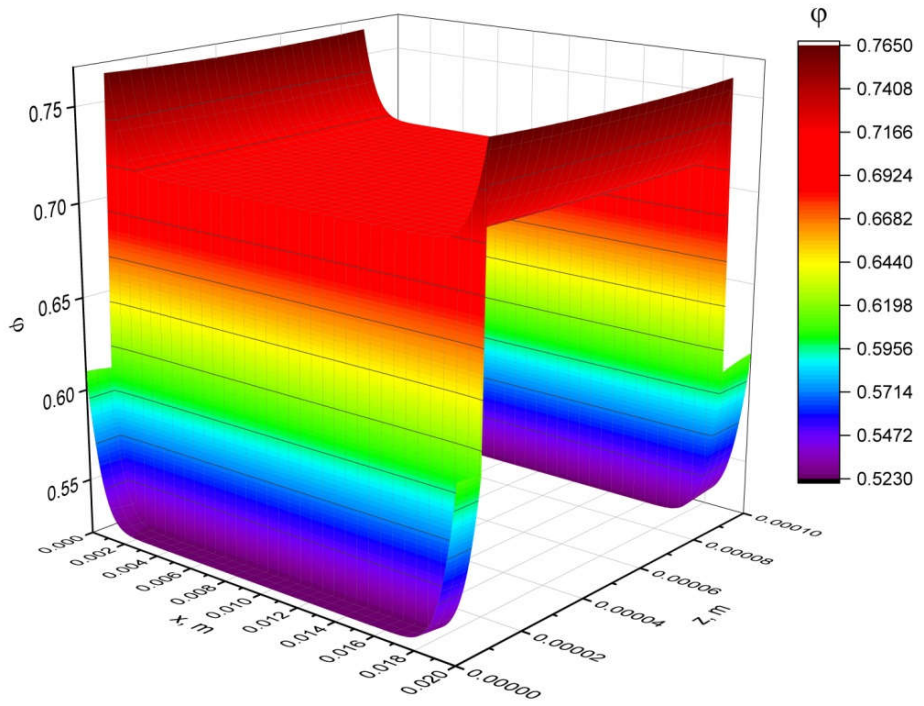


(**a**)

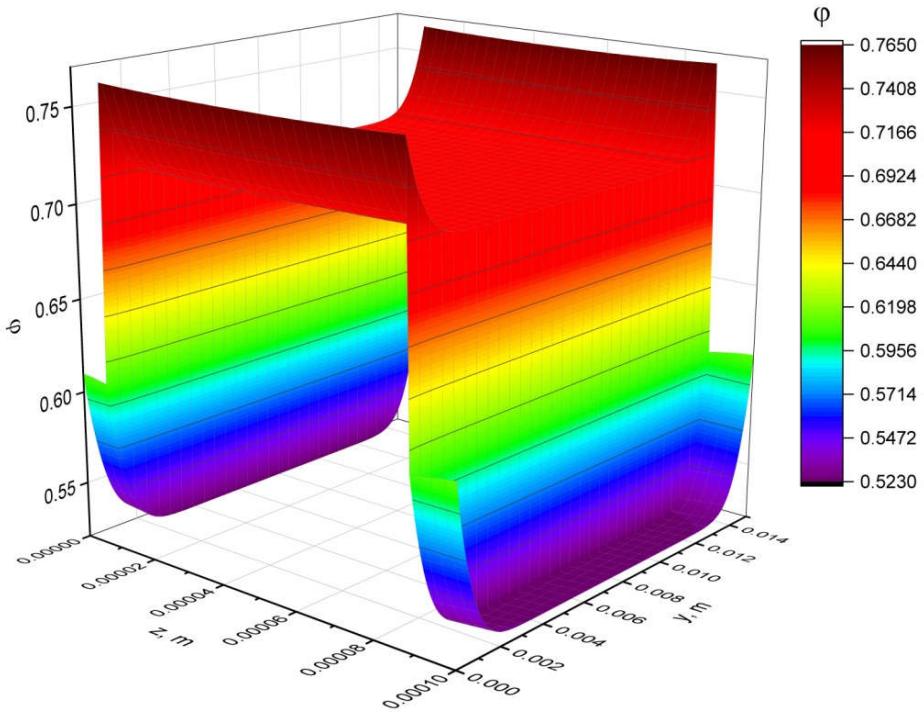


(**b**)

Figure 9. Distribution of water in the xz (**a**) and yz (**b**) plane of a birch leaf (T_{ff} = 1000 K, t = 3 s).



(**a**)



(**b**)

Figure 10. Distribution of the vapor-gas mixture in the xz (**a**) and yz (**b**) planes of a birch leaf (T_{ff} = 1000 K, t = 3 s).

Figures 3–10 show the planes xy, xz and yz in sections passing from middle point of birch leaf. Figures 3 and 4 show typical patterns of temperature distribution in the birch leaf. The sample is warmed up more at the border of contact with the environment. The areas in the middle of the leaf are less heated, which is due to the presence of moisture in the sample and indirect contact with the high-temperature environment. The nature of the temperature distribution corresponds to the nature of the solved equation during simulation.

Figures 5–10 allow one to evaluate the dynamics of the phases' behavior in a forest fuel sample exposed to a high-temperature environment. As can be seen from the figures, the pyrolysis is accompanied by the matter decomposition reaction. Such reaction leads to the release of gaseous products. It is noted that during the considered exposure time about a half of the initial of the dry organic matter amount decomposes. The distributions show that thermal decomposition is not uniform, but begins at the boundaries of the sample where it is in contact with the environment. As for the process of moisture evaporation from the sample, it can be noted that this process is already actively going on at a process time of 0.2 s (3/4 of the total moisture content in the sample has evaporated). By the end of the period under review, this process has been fully completed.

The obtained two-dimensional distributions over different sample planes make it possible to obtain a general understanding of heat and mass transfer processes occurring in the birch leaf when exposed to a high-temperature medium.

Different exposure times, namely, 0.1, 0.2, 0.3, 0.5, 1, 2, 3, 5 s were considered. The obtained results revealed that the pyrolysis induction period reaches 2 s, depending on the exposure time to a high-temperature environment. An inert heating of a forest fuel sample occurs first. Then the process of moisture evaporation begins. Higher temperatures provoke the thermal decomposition process to begin. The characteristic process times (0.2 and 3 s) were chosen to demonstrate the typical distributions of the volume phases fractions in a forest fuel sample before and after intense decomposition. According to the experimental data [50], at this time, a forest fuel sample is actually subject to flame combustion in the gas phase. Thus, it makes no sense to present calculations for more than 3 s in this work. According to the developed mathematical model, the sample continues to intensively thermally decompose deep into the leaf. The front of thermal decomposition gradually moves towards the middle of the sample. In principle, tracing the advance of the thermal decomposition front into the depth of the sample will enable judgement about a decrease in the sample size. The value of the dry organic matter fraction can serve as a criterion for assessing the destruction of a part of forest fuel sample. If the dry organic matter fraction equals zero, this means a complete leaf destruction has taken place under the influence of the high-temperature environment. It should be noted that, in reality, any forest fuel cannot be completely burned up, since the mineral part remains and there is underburning. This fact can be accounted for in the mathematical model by entering the underburning coefficient. In a current mathematical model this is not essential. The underburning coefficient is determined experimentally by burning various forest fuels: a forest fuel sample is weighed before and after burning with the rest of the burned sample in a chemical container. Carrying out experiments with typical forest fuels of a particular forest stand will make it possible to obtain a database on the underburning coefficients and subsequently use them in the practical application of the developed mathematical model.

Experimental studies of birch leaf ignition in a tube furnace were carried out earlier [50]. According to the experimental procedure, a sample was placed in the tube furnace channel until its flame combustion. The high-speed video camera allowed registration of all the processes occurring in the tube furnace. The moments of the gaseous pyrolysis products formation and release, accompanied by the formation of soot particles, were visually determined [65]. Birch leaf ignition in the gas phase also occurred. It was found, that pyrolysis of dry organic matter occurs at times of about 0.2–1 s [50]. All other things being equal, it is theoretically established in this article that pyrolysis occurs at times of the order of 0.7–1.9 s. The difference in theoretical values averaged 0.65 s for various simulation

scenarios. Such differences are explained by the fact that a pre-dried forest fuel sample was used in the experiment. In this article, a forest fuel element with a non-zero moisture value was used. In the framework of this study, a birch leaf, which contains moisture in the central layer, is considered. The paper considers a scenario when a leaf broke off a tree branch and fell to the soil surface. Moisture exchange processes typical for a living leaf are not considered. It is clear that the error of the mathematical model is not small. First, this is due to the difference in conditions in the experiment performed. Secondly, forest fuel material is a complex heterogeneous object with a developed multi-scale porous structure [66]. Modeling such objects is not a trivial task. According to [67], the error of mathematical models in the theory of forest fires ranges from 30% to 580%. Therefore, the results obtained can be considered satisfactorily consistent with the results of the experiment [50].

5. Discussion

The obtained results are intended to improve the prediction of forest fire danger [68–73]. Such programs as RAD Studio [74], but also Matlab [75] or MS Visual Studio [76] are suitable for implement the calculations. The developed mathematical model enables modernization or replacement of systems for predicting forest fire danger [77–80]. In addition, the technologies of mathematical modeling, geoinformation technologies, and remote sensing data can be integrated into a big multifunctional system [81–84].

It must be said that the proposed mathematical model is optimal for implementation as a component of a big prediction systems. The model quite simply takes into account the moisture evaporation from the forest fuel element by means of a simple kinetic scheme. A group of mathematical models of fuel drying [25,85,86] of different complexities was formulated earlier. Models consider a fairly wide range of parameters of forest fuel and the external environment. For example, these models take into account the incident and reflected radiation from the sun, the angle of inclination of the underlying surface, and convective and conductive heat exchange with the external environment. However, in the case of crown forest fire, many parameters and processes are redundant and need not be taken into account.

It should be mentioned that complex mathematical models of forest fuel drying are quite demanding on computational resources. Even for a simplified zero-dimensional mathematical model [86], multiprocessor computing systems are required [59] in controlled areas on the scale of forestry [87]. When predicting crown forest fires, it is extremely important to minimize the time for obtaining predictive information so that there is a sufficient period of catastrophe anticipation when a crown forest fire moves to an industrial or transport facility, or settlement [88].

A similar situation is observed when modeling the pyrolysis of forest fuel exposed by a crown forest fire. The various rather complex and complete mathematical models indicated in the overview section will require significant computing resources when applied on the scale of even one forest [57]. In addition, a large set of input data for such models is needed to calculate the forest fuel behavior in real conditions. Therefore, the mathematical model proposed in this paper will allow the use of less powerful computing systems since it is based on a global one-stage kinetic scheme. Alternatively, it will provide faster and more frequent predictive information on the forest fuel's behavior.

The deterministic-probabilistic method has been proposed for application in predicting forest fire danger [89]. Within this approach, the prediction has two components. The first component describes the random nature of causes of the forest fires and enables calculation of the probabilities of thunderstorm activity [90] and anthropogenic load [91]. The deterministic component allows simulation of a specific scenario of heat and mass transfer when exposed to a source of elevated temperature [92,93].

Currently, various approaches are used to assess forest fire danger, including deterministic, probabilistic, simulation, statistical, and empirical approaches [94–98]. For over 10 years, Tomsk Polytechnic University has been developing an integrated deterministic-probabilistic approach for forest fire danger prediction [99]. Such approach allows assess-

ment of the probability of any scenario of a dangerous fire situation. The scenario itself is modeled deterministically. Typical examples of deterministic mathematical models are presented in [100,101]. Probability formulas are considered in [102,103]. The implementation of the mentioned approach to forecasting forest fires from thunderstorms is presented in [104]. Pyrolysis is an important stage prior to the onset of a forest fire. Therefore, it is important to understand what processes take place in forest fuels before ignition. The mathematical model developed in this work can be used both for predicting forest fire danger and further environmental consequences (so-called fire risk). For risk prediction, it will be necessary to improve the mathematical model by adding a block of chemical reactions in the gas phase. Next year, it is planned to initiate a research project to study forest fuel ignition using experimental equipment—a thermal imager and a gas analyzer, which will allow us to develop and verify a mathematical model of forest fuel ignition by a high-temperature environment. By analogy with [104], probabilistic formulas will be developed to relate the ignition delays, thermophysical and thermokinetic parameters to the ignition probability. The interval of change in the probability of forest fuel ignition will be divided into several subintervals for a qualitative assessment of forest fire danger. For example, the following levels of forest fire danger can be distinguished: extreme, high, moderate, low, no fire danger [104]. In terms of environmental consequences, the presented mathematical model can be improved by adding a block of soot formation [65] and the formation of aerosol particles. In this case, the mathematical model can be used for theoretical estimates of the emission of soot and aerosol particles from forest fires. Both cases of such practical use of the mathematical model assume software implementation in a high-level programming language (for example, Delphi, Matlab). Moreover, it is necessary to organize additional processing of data on a specific forest area using GIS systems. For these purposes, ArcGIS, QGIS, and Origin Pro [105–107] can be used. In the future, predictive information can be used by forest fire protection services to make specific management decisions.

The main innovative element of this work is the use of deterministic modeling to develop methods for predicting forest fires and their environmental consequences. This is a rather laborious task that requires complex theoretical and experimental research, since many parameters or initial data for the mathematical model are determined by experiment. Hence, many researchers abandon using such methods and use data mining or neural network technologies, that is, so-called soft computing [108–110]. However, such approaches can give rise to big errors in case of sudden changes, for example, in weather conditions. This is especially true in the case of climate change, when extreme weather events can occur in an area that was not previously affected by such an impact. In this case, only complex deterministic-probabilistic mathematical models can provide a more or less adequate predictive assessment of forest fire danger.

This study reveals the patterns of temperature increase at a specific point of a leaf over time. The first stage is characterized by a more significant temperature increase in comparison with subsequent stages. The temperature in the considered point increases by about 300 K, 200 K and 100 K at an exposure time of 1, 2 and 3 s, respectively. This pattern is explained by the beginning of the pyrolysis process, which requires a certain amount of heat for the release of the gaseous products. The obtained results permit analysis of temperature changes as well as control of the ratio of the gas and solid phases. The proposed models also can help with the determination of the ignition delay time since it is possible to describe not only the drying and pyrolysis processes but also the interaction between gaseous products and the oxidizer. Both crown and surface forest fires can occur due to the processes of sample heating, moisture evaporation and pyrolysis. These processes depend on the patterns of the heat and mass transfer in the typical forest fuel elements (needles or leaf) since they determine the evolution of chemical composition of gas products near the location of the ignition. It is also necessary to consider the layered structure of the leaf, which can influence its temperature distribution and the beginning of the pyrolysis process. This is due to the fact that all layers need to be heated for the gaseous products to be released. If there are no fresh volatiles, there is no opportunity for ignition and further

stable burning. This leads us to the conclusion that the heat transfer regime significantly influences the pyrolysis rate and, accordingly, the further ignition and fire spread over the tree crown in relation to the forest fuel layers near the ground. This issue is extremely important in the context of mixed forest stands.

The typical peculiarities of the birch leaf pyrolysis in the context of their influence on a crown forest fire were considered in this study for the first time. Such knowledge is quite important because of the huge distribution area of birch. It covers almost the entire forest territory of the Russian Federation. Moreover, such species are typical for boreal forests. It means that the obtained results can be applied for forested areas in European countries, USA and Canada.

The proposed model can be improved by adding other important patterns of considered processes such as the multi-stage mechanism of moisture evaporation and the three-component composition of dry organic matter (lignin, cellulose, hemicellulose). Further, the considered sample could be a porous medium.

There are several groups of tasks in fighting forest fires. The first group is aimed at monitoring and predicting forest fire danger. The second group is related to the localization and extinguishing of the fires. The third group of tasks is connected with the assessment of damage from forest fires, as well as with measures to restore damaged forest areas. Each group of tasks is important in terms of minimizing damage from forest fires. This is equally true for the Russian Federation, Canada, Australia or the countries of Southern Europe [111–125]. Perhaps, for the Mediterranean region, these tasks are even more important, since catastrophic forest fires have been observed there in recent years. An analysis of the practice of extinguishing forest fires, in the Russian Federation, for example, shows the low efficiency of existing technologies. Often, a forest fire continues to spread until it meets a natural barrier in the form of a river bed, swamps, or a deforested mountain range. Forest fires sometimes continue to remain in the active phase until a large amount of precipitation falls. It must be assumed that the greatest success in fighting forest fires can be achieved at the stage of their prediction, including using the deterministic mathematical model of pyrolysis of a forest fuel element as discussed in this article. Timely and high-quality forecasts will help plan measures to prevent forest fires, including the distribution of forest firefighters in the vicinity of the most fire-prone areas of forests. In addition, knowing the expected areas of forests with a high probability of forest fires, scenarios can be calculated for estimating pollutant emissions and the approximate burnt area of forests.

6. Conclusions

As part of the research work, scenario numerical modeling of the processes of heat and mass transfer in a single forest fuel element (birch leaf) exposed to a high-temperature environment was carried out.

As a result, the following tasks were solved:

(1) A mathematical model of heat and mass transfer has been developed in the framework of a three-dimensional statement taking into account pyrolysis and moisture evaporation.
(2) Scenario numerical modeling was carried out and the obtained results were analyzed.

The proposed mathematical model will make it possible to develop new or modernizes systems for predicting forest fire danger using the deterministic-probabilistic approach. The operating experience of the Canadian Forest Fire Danger Rating System presented in a number of publications shows that the use of prediction systems leads to a decrease in both environmental and social-economic damage. The prediction of forest fire danger is the first and most important stage in the fight against forest fires.

The developed model is implemented in the high-level programming language Delphi. RAD Studio software was used for conducting calculations. The developed console application can be used with GIS systems to visualize predictive information taking into account spatial localization.

This study provides the results of mathematical modeling of pyrolysis in forest fuel element exposed to a high-temperature medium. Particular attention is paid to the scenario of crown forest fires since it is difficult to conduct experimental studies for these conditions. Such experiments imply danger for the personnel who conduct such research as well as difficulties in creating such conditions. For this reason, mathematical simulation is the best approach. The numerical research carried out showed the conditions of thermal decomposition of a typical forest fuel (birch leaf). This is extremely important in the case of forest fire prediction in mixed forests. The main attention is paid to the pyrolysis process since it determines the flux of gaseous products into the area of increased temperature. Three levels of forest fuels may be considered: a single element of forest fuel, a layer and a complex of several forest fuels. The present study of fundamental processes in a single element of forest fuel will enable a transition to the levels of a the complex of forest fuels.

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