Abstract: This paper is devoted to the problem of development of a mathematical model for the description of heat and mass transfer processes at crown forest fire initiation and spread. The mathematical model of forest fire was based on the analysis of experimental data and using concepts and methods from reactive media mechanics. This study gives a two-dimensional averaged mathematical setting and method of numerical solution of a problem of forest fire spread. The boundary-value problem is solved numerically using the method of splitting according to physical processes. It was based on numerical solution of two-dimensional Reynolds equations for the description of turbulent flow taking into account for diffusion equations chemical components and equations of energy conservation for gaseous and condensed phases. In this context, the study - mathematical modeling - of the conditions of forest fire spreading that would make it possible to obtain a detailed picture of the change in the velocity, temperature and component concentration fields with time, and determine as well as the limiting conditions of forest fire propagation is of interest.

Key-Words: Mathematical model, forest fire, ignition, combustion, control volume, discrete analogue.

1 Introduction
A great deal of work has been done on the theoretical problem of forest fire initiation. Crown fires are initiated by convective and radiative heat transfer from surface fires. However, convection is the main heat transfer mechanism. The first explanation of this process was given by Van Wagner [1]. The theory proposed there depends on three simple crown properties: crown base height, bulk density, and moisture content of forest fuel. Also, crown fire initiation and hazard have been studied and modeled in detail (see for example Alexander [2]; Van Wagner [3]; Xanthopoulos [4]; Rothermel [5]; Cruz and others [6]; Albini and others [7]; Scott and Reinhardt [8]). The more complete discussion of the problem of modeling forest fires is provided by a cycle of works produced by a group of coworkers at Tomsk University (Grishin [9]; Grishin and Perminov [10]; Perminov [11,12]). In particular, a mathematical model of forest fires was obtained by Grishin [9] based on an analysis of known and original experimental data (Grishin [9]; Konev [13]), and using concepts and methods from reactive media mechanics. The physical two-phase models used by Morvan and Dupuy [14,15] may be considered as a continuation and extension of the formulation proposed in [9].

2 Problem Formulation
The basic assumptions adopted during the deduction of equations, and boundary and initial conditions: 1) the forest represents a multi-phase, multistoried, spatially heterogeneous medium; 2) in the fire zone the forest is a porous-dispersed, two-temperature, single-velocity, reactive medium; 3) the forest canopy is supposed to be non-deformed medium (trunks, large branches, small twigs and needles), which affects only the magnitude of the force of resistance in the equation of conservation of momentum in the gas phase, i.e., the medium is assumed to be quasi-solid (almost non-deformable during wind gusts); 4) let there be a so-called “ventilated” forest massif, in which the volume of fractions of condensed forest fuel phases, consisting of dry organic matter, water in liquid state, solid pyrolysis products, and ash, can be neglected compared to the volume fraction of gas phase (components of air and gaseous pyrolysis products); 5) the flow has a developed turbulent nature and molecular transfer is neglected; 6) gaseous phase density doesn’t depend on the pressure because of the low velocities of the flow in comparison with the velocity of the sound. Let the coordinate reference point \(x_1, x_2, x_3 = 0\) be situated at the centre of the surface forest fire source at the height of the roughness level, axis \(0x_1\) directed parallel to the Earth’s surface in the direction of the unperturbed wind speed, axis \(0x_2\) directed perpendicular to \(0x_1\) and axis \(0x_3\) directed upward (Fig. 1).
Because of the horizontal sizes of forest massif more than height of forest \( - h \), system of equations of general mathematical model of forest fire [9] was integrated between the limits from height of the roughness level - 0 to \( h \). Besides, suppose that

\[
\int_0^h \phi \, dx = \phi h
\]

\( \phi \) - average value of \( \phi \). The problem formulated above is reduced to a solution of the following system of equations:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_{j})}{\partial x_{j}} = Q - (\dot{m} - \dot{m}^{*})/h, \quad j = 1,2,3;
\]

\[
\rho \frac{dv_{j}}{dt} = -\frac{\partial \rho}{\partial x_{j}} + \frac{\partial}{\partial x_{j}} (\rho v_{j} v_{l}) - \rho c_{d} v_{j} |v| - \rho g_{l} - \rho Q_{v}, \quad j = 1,2,3;
\]

\[
\rho \frac{dT}{dt} = \frac{\partial}{\partial x_{j}} (\rho c_{p} T/v_{j}) + q_{R} + c_{a} (T - T_{a}) + k(T - T_{s});
\]

\[
\frac{d\alpha_{p}}{dt} = \alpha_{p} \pi_{f} T_{S} = q_{3} R_{s} - q_{3} R_{s} + k(c U_{R} - 4\sigma T_{a}^{4}) + (q_{3} R_{s} - q_{3} R_{s})/h = 0;
\]

\[
\sum_{i=1}^{33} \nu_{i} \nu_{k} \nu_{l} \nu_{m} \nu_{n} \nu_{o} \nu_{p} \nu_{q} \nu_{r} \nu_{s} \nu_{t} \nu_{u} \nu_{v} \nu_{w} \nu_{x} \nu_{y} \nu_{z} = (v_{1}, v_{2}, v_{3}), \quad \hat{g} = (0,0,g).
\]

The system of equations (1)–(7) must be solved taking into account the initial and boundary conditions

\[
t = 0 : \quad v_{1} = 0, \quad v_{2} = 0, \quad v_{3} = 0, \quad T = T_{a}, \quad c_{a} = c_{a_{0}}, \quad T_{s} = T_{a}, \quad \phi_{0} = \phi_{a_{0}};
\]

\[
x_{1} = -x_{1} : \quad v_{1} = V_{1}, \quad v_{2} = 0, \quad \frac{\partial v_{1}}{\partial x_{1}} = 0, \quad T = T_{a}, \quad c_{a} = c_{a_{0}};
\]

\[
-x_{2} = x_{2} : \quad \frac{\partial v_{1}}{\partial x_{2}} = 0, \quad \frac{\partial v_{2}}{\partial x_{2}} = 0, \quad \frac{\partial v_{3}}{\partial x_{2}} = 0, \quad \frac{\partial c_{a}}{\partial x_{2}} = 0, \quad \frac{\partial T}{\partial x_{2}} = 0, \quad \frac{c_{a} U_{g}}{3k} \frac{\partial U_{g}}{\partial x_{2}} + \frac{c_{a} U_{g}}{2} = 0;
\]

\[
x_{3} = x_{3} : \quad \frac{\partial v_{1}}{\partial x_{3}} = 0, \quad \frac{\partial v_{2}}{\partial x_{3}} = 0, \quad \frac{\partial v_{3}}{\partial x_{3}} = 0, \quad \frac{\partial c_{a}}{\partial x_{3}} = 0, \quad \frac{\partial T}{\partial x_{3}} = 0, \quad \frac{c_{a} U_{g}}{3k} \frac{\partial U_{g}}{\partial x_{3}} + \frac{c_{a} U_{g}}{2} = 0.
\]

Here and above \( \frac{d}{dt} \) is the symbol of the total (substantial) derivative; \( \alpha_{p} \) is the coefficient of phase exchange; \( \rho \) - density of gas – dispersed phase, \( t \) is time; \( v_{l} \) - the velocity components; \( T, T_{a} \) - temperatures of gas and solid phases, \( U_{g} \) - density of radiation energy, \( k \) - coefficient of radiation attenuation, \( p \) - pressure; \( c_{p} \) - constant pressure specific heat of the gas phase, \( c_{p_{s}}, \rho_{s}, \phi_{s} \) - specific heat, density and volume of fraction of condensed phase (1 – dry organic substance, 2 – moisture, 3 – condensed pyrolysis products, 4 – mineral part of forest fuel), \( R_{l} \) – the mass rates of chemical reactions, \( q_{i} \) – thermal effects of chemical reactions; \( k_{g}, k_{S} \) - radiation absorption coefficients for gas and condensed phases; \( T_{a} \) - the ambient temperature; \( c_{a} \) - mass concentrations of \( \alpha \) - component of gas - dispersed medium, index \( \alpha =1,2,3 \), where 1 corresponds to the density of oxygen, 2 - to carbon monoxide CO, 3 - to carbon dioxide and inert components of air; \( R \) – universal gas constant; \( M_{a}, M_{G} \) and \( M \) molecular mass of \( \alpha \) - components of the gas phase, carbon and air mixture; \( g \) is the gravity acceleration; \( c_{d} \) is an empirical coefficient of the resistance of the vegetation, \( s \) is the specific surface of the forest fuel in the given forest stratum. To define source terms which characterize inflow (outflow of mass) in a volume unit of the gas-dispersed phase, the following formulae were used for the rate of formulation of the gas-dispersed mixture \( m \), outflow of oxygen \( R_{51} \), changing carbon monoxide \( R_{52} \).

\[
Q = (1 - \alpha_{c}) R_{1} + R_{2} + \frac{M_{1}}{M_{a}} R_{3}, \quad R_{51} = -R_{51} - \frac{M_{1}}{2M_{2}} R_{52} - R_{S5}, \quad R_{52} = v_{g} (1 - \alpha_{c}) R_{1} - R_{5}, \quad R_{S5} = 0.
\]

Here \( v_{g} \) – mass fraction of gas combustible products of pyrolysis, \( \alpha_{c} \) and \( \alpha_{c} \) – empirical constants. Reaction rates of these various contributions (pyrolysis, evaporation, combustion of coke and volatile combustible products of pyrolysis) are approximated by Arrhenius laws whose parameters (pre-exponential constant \( k_{i} \) and activation
energy $E_0$) are evaluated using data for mathematical models [9,11].

$$R_1 = k_1 \rho_1 \phi_1 \exp\left(-\frac{E_1}{RT}\right),$$

$$R_2 = k_2 \rho_1 \phi_2 \exp\left(-\frac{E_2}{RT}\right),$$

$$R_3 = k_3 \rho_3 \phi_3 \rho_c \exp\left(-\frac{E_3}{RT}\right),$$

$$R_4 = k_4 \rho_4 \phi_4 \rho_c \exp\left(-\frac{E_4}{RT}\right).$$

The initial values for volume of fractions of condensed phases are determined using the expressions:

$$\phi_{i0} = \frac{d(1-v_i)}{\rho_i},$$

$$\phi_{x0} = \frac{\rho_l}{\rho_i},$$

$$\phi_{e0} = \alpha \rho_1 \rho_l,$$

where $d$ - bulk density for surface layer, $v_i$ – coefficient of ashes of forest fuel, $W$ – forest fuel moisture content.

It is supposed that the optical properties of a medium are independent of radiation wavelength (the assumption that the medium is “grey”), and the so-called diffusion approximation for radiation flux density were used for a mathematical description of radiation transport during forest fires.

To close the system (1)–(7), the components of the tensor of turbulent stresses, and the turbulent heat and mass fluxes are determined using the local-equilibrium model of turbulence (Grishin, [9]). The system of equations (1)–(7) contains terms associated with turbulent diffusion, thermal conduction, and convection, and needs to be closed. The components of the tensor of turbulent stresses $\rho_v^T$, as well as the turbulent fluxes of heat and mass $\rho v_j^T$, $\rho v_j^c$ are written in terms of the gradients of the average flow properties using the formulas

$$-\rho v_j^T = \mu_i \left(\frac{\partial^2 v_j}{\partial x_j} + \frac{\partial^2 v_i}{\partial x_i}\right) \frac{2}{3} K \delta_{ij},$$

$$-\rho v_j^c = \lambda_i \frac{\partial T}{\partial x_j},$$

$$\lambda_i = \mu_i c_p / \rho_f,$$

where $\mu_i$, $\lambda_i$, $D_i$ are the coefficients of turbulent viscosity, thermal conductivity, and diffusion, respectively; $Pr$, $Sc$ are the turbulent Prandtl and Schmidt numbers, which were assumed to be equal to 1. In dimensional form, the coefficient of dynamic turbulent viscosity is determined using local equilibrium model of turbulence [9].

The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different (for example pine [9,11,13]) type of forest. The system of equations (1)–(7) must be solved taking into account the initial and boundary conditions. The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different type of forest; for example, pine forest (Grishin, Perminov [11]).

### 3 Calculation Method and Results

The boundary-value problem (1)–(7) is solved numerically using the method of splitting according to physical processes (Perminov [11]). In the first stage, the hydrodynamic pattern of flow and distribution of scalar functions was calculated. The system of ordinary differential equations of chemical kinetics obtained as a result of splitting was then integrated. A discrete analog was obtained by means of the control volume method using the SIMPLE like algorithm (Patankar [16])

The accuracy of the program was checked by the method of inserted analytical solutions. Analytical expressions for the unknown functions were substituted in (1)–(7) and the closure of the equations were calculated. This was then treated as the source in each equation. Next, with the aid of the algorithm described above, the values of the functions used were inferred with an accuracy of not less than 1%. The effect of the dimensions of the control volumes on the solution was studied by diminishing them. The time step was selected automatically.

Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically. The distribution of basic functions shows that the process of crown forest fire initiation goes through the next stages. The first stage is related to increasing maximum temperature in the ground cover with the result that a surface fire source appears. At this process stage over the fire source a thermal wind is formed a zone of heated forest fire pyrolysis products which are mixed with air, float up and penetrate into the crowns of trees. As a result, forest fuels in the tree crowns are heated, moisture evaporates and gaseous dispersed pyrolysis products are generated. Ignition of gaseous pyrolysis products of the ground cover occurs at the next stage, and that of gaseous pyrolysis products in the forest canopy occurs at the last stage. As a result of heating of forest fuel elements of crown, moisture evaporates, and pyrolysis occurs accompanied by the release of gaseous products, which then ignite and burn away in the forest canopy. At the moment of ignition the gas combustible products of pyrolysis burns away, and the concentration of oxygen is rapidly reduced. The temperatures of both phases reach a maximum value at the point of ignition. The ignition processes is of a gas-phase nature. Note also that the transfer of energy from the fire source takes place due to radiation; the value of radiation heat flux density is small compared to that of the convective heat flux. In the vicinity of the source of heat and mass release, heated air masses and products of pyrolysis and combustion float up. At $V_c \neq 0$, the wind field in the forest canopy interacts with the gas-jet obstacle that forms from the surface forest fire source and from the ignited forest canopy base and burn away in the forest canopy. In the vicinity of the source of heat and mass release, heated air masses and products of pyrolysis and combustion float up. At $V_c \neq 0$, the wind field in the
forest canopy interacts with the gas-jet obstacle that forms from the surface forest fire source and from the ignited forest canopy base. On the windward side the movement of the air flowing past the ignition region accelerates. Figures 2a,b, 3a,b and 4a,b present the distribution of temperature $\bar{T} (\bar{T} = T / T_e, T_e = 300 K)$ (1-5, 2 - 4.5, 3 - 4, 4 - 3.5) for gas phase, oxygen $\bar{c}_1 (1 - 0.5, 2 - 0.7, 3 - 0.8)$, volatile combustible products of pyrolysis $\bar{c}_2$ concentrations (1 - 0.05, 2- 0.1, 3 – 0.5) ($\bar{c}_2 = c_{2e} / c_{1e}, c_{1e} = 0.23$) for wind velocity $V_e = 10 \text{ m/s}$ and a) $t=3$ sec., b) $t=5$ sec. We can note that the isotherms is moved in the forest canopy and deformed by the action of wind. Similarly, the fields of component concentrations are deformed. It is concluded that the forest fire begins to spread.
4 Conclusion

The results of calculation give an opportunity to evaluate critical condition of the forest fire spread, which allows applying the given model for preventing fires. It overestimates the crown forest fire spread that depends on crown properties: bulk density, moisture content of forest fuel and etc. The model proposed there give a detailed picture of the change in the velocity, temperature and component concentration fields with time, and determine as well as the influence of different conditions on the crown forest fire initiation. The results obtained agree with the laws of physics and experimental data.

References

[14] Morvan, D., Dupuy J.L., Modeling of fire spread

Moisture content of FF in crown is W=110% and d=0.2 kg/m³.

