An initiation of forest fires as a result of gas pipeline accidents

Valeriy A. Perminov, Elina Soprunenko

Abstract— Accidents occurring at the sites of pipelines are accompanied by environmental damage, economic loss, and sometimes loss of life. In some cases, the pipelines transporting fuel are ruptured as a result of accidents. The resulting gas cloud expands over nearby forests or homes and ignited, creating a large fireball. As a result of this processes heat radiation is emitted, it heats and ignites the forest combustible materials in the forest. The paper gives a new mathematical setting and method of numerical solution of a problem of a forest fire initiation as a result of accident. The boundary-value problem is solved numerically using the finite volume method and method of splitting according to physical processes. The dependence of the sizes of forest fire zones for different amounts of leaked flammable substances and moisture content, bulk and type of vegetation were studied. In this paper, we calculated the sizes of the possible ignition zones in emergency situations on pipelines located close to the forest, accompanied by the appearance of fireballs. The paper suggested in the context of the general mathematical model of forest fires is given a new mathematical setting, method and results of numerical solution.

Keywords—accident**,** fireball**,** forest fire, ignition, mathematical model, pipeline, radiation.

I. Introduction

As a rule, a large man-made catastrophe in the trunk pipelines accompanied by the appearance of fireballs, which under the influence of possible ignition nearby vegetation. In this connection, it is interesting to predict the occurrence and development of fires that occurred in the vicinity of the place of an emergency. Since the full-scale studies in solving these problems is not possible, are actual methods of mathematical modeling. In the mathematical model used, the integral parameters (the maximum size of the fireball lifetime and lifting height of the burning clouds, the radiation power per unit area) as a function of the mass of fuel involved, derived from empirical relationships by treating the experimental results and the rapid analysis of accidents [1-3].

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V. A. Perminov is with the Tomsk Polytechnic University, Tomsk, Lenin avenue, 30, Russia 634050 (corresponding author, e-mail: perminov@tpu.ru).

Elina Soprunenko. He is now with the Department of Ecology and Basic Safety, Tomsk Polytechnic University, Tomsk, Lenin avenue, 30, Russia 634050 (e-mail: soprunenko.elina@yandex.kz).

II. THE PHYSICAL AND MATHEMATICAL MODEL

Consider that the source of radiant energy is at a height H of the Earth's surface (see Fig. 1). Since its dimensions are small compared to the radius of the Earth, we assume that a point source of radiation, D - the distance from the source to the center point of the surface of the forest, h - the height of forest, 0 - pipeline. On the upper boundary $z = h$ forest acts intense radiant flux $q_R\ (r,\ t)$, which is attenuated with increasing distance from the epicenter 0 Maximum intensity of the source is reached at $t = t_m$, further, it decays to zero according to $q_R(r,t)$, which can be approximated as follows: [1,2,4]

$$q_R(r,t) = \frac{t_p P_m \sin L}{4\pi D^2} \begin{cases} t/t_m, & ,\ t < t_m \\ \exp(-k_0(t/t_m - 1)), & t \ge t_m \end{cases}, \quad (1)$$

$$t_m = 0.92 \times M_f^{0.303},\ \text{s};\ P_m = 450 \times 10^3\ J \bullet s^{-1}.$$

Here t_m- the moment of time at which the fireball reached its maximum size, s; D - distance from the radiation source to the forest canopy, m; t_p - the transmittance of the atmosphere; P_m- maximum value of a light pulse at time t_m, L - the angle between the vector of the radiation flux density and an upper limit of vegetation; k_0 - approximation coefficient (k_0 = 0.75); M_f – mass of fuel involved.

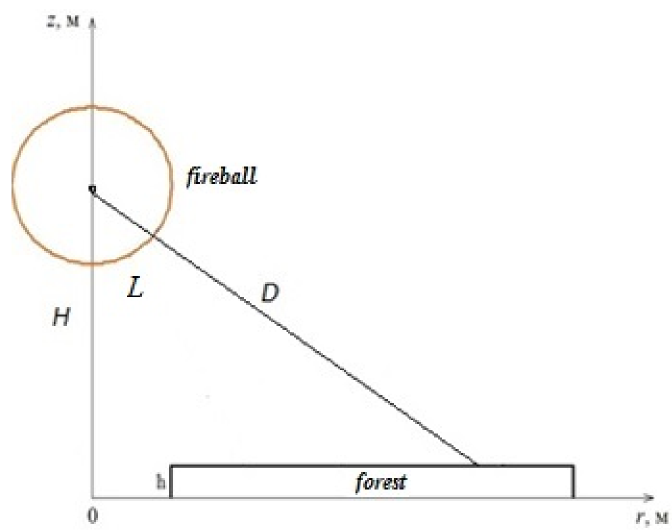

Fig. 1. The scheme of domain.

Receipt of radiant energy in the vegetation cover ($z_o \le z \le h$) causes heating of forest fuel, evaporation and subsequent thermal decomposition of the solid material with the release of the volatile pyrolysis products, which then ignite. Due to the presence of gravity, the heated air volumes begin to emerge up, so processes surround the ignition of forest vegetation are, in general, related to the hydrodynamics of the flow. Due to the fact that at the periphery of the epicenter intensity of the radiant flux in the forest canopy is small, there is no ignition. Thus, during the action of the radiation source is formed by this initial ignition forest radius r_*. Ideally, it has a circular shape in plan. Its subsequent development is determined by the interaction of ascending currents of the wind field as they make the surface layer of the atmosphere and carried a spread in the surrounding area of burning solid elements, as well as meteorological and geographical conditions in a given area. [3].

For the purposes of this study, we assume that the wind velocity in the atmosphere is relatively low and the energy is mainly transferred by radiation. This allows us to consider the problem in the axisymmetric formulation. Since the combination of different physical factors accompanies the ignition process of the forest, it is advisable to carry out the description at different levels of complexity. The hierarchy of physical models, including more complex to evaluate the role of individual factors that are omitted to simplify the description of the phenomenon [3]. The paper will be given basic physical assumptions and representations of the object of research needed to understand the mathematical model. It is believed that: for symmetric about the vertical axis z, having started in the center of the area under consideration (Figure 1) and directed vertically upward, the flow is developed turbulent and molecular transport is neglected in comparison with the turbulent, gas phase density does not depend on pressure because the flow velocity is small in comparison with the speed of sound, the forest canopy is considered to be non-deformable medium. We assume that the forest canopy can be modeled by a uniform two-temperature multiphase porous reactive medium. Provided the temperature of condensed (solid) T_s and T gas phase. The first is the dry organic matter, moisture, condensed pyrolysis products and mineral part of forest fuels. In the gas phase will be distinguished only necessary to describe the combustion reaction components, i.e. the mass concentrations c_α (α = 1 - oxygen, 2 - combustible pyrolysis products are wood fuels, 3 - other inert ingredients, including water vapor). The solid phase, which combustible material (thin needles and twigs of up to 6 mm), water in liquid state and drip-condensed pyrolysis products has its own velocity and the volume fraction, when compared with the gas phase can be neglected in the appropriate equations as per unit volume of wood is <0.5 kg. From the standpoint of hydrodynamics, this porous medium, nevertheless, offers resistance to any force $\vec{F} = \rho s c_d |\vec{v}|\vec{v}$ displacement of air masses. It is believed that the medium is locally thermodynamic equilibrium. Turbulent convective transport due to the action of gravity, is described with the Reynolds equation [3]. We will also take into account the physical and chemical processes occurring in the forest canopy, the rate of chemical reactions which R_i (i = 1, 2, 3, 5) as a function of temperature and other parameters assumed to be known. Determining the mechanism of energy transfer in this case is the radiation. In the forest canopy absorbs, reflects and emits mainly solid phase. To describe transport in such a specific Continuum will use the diffusion approximation. This is justified, since the mean free path of the radiation in the canopy $l_R << l_o$, $l_0 \sim$ 10-15 м, $l_R \sim$ 1 m (*lo* - the characteristic scale height) [3]. We direct the z-axis vertically upwards r-axis along the earth's surface (see Fig. 1). To describe the heat and mass transfer in the amount of forest vegetation with the general conservation laws are used for the multiphase medium. Since any movement of air currents in the atmosphere is turbulent, then to describe them using the Reynolds equation. The problem formulated in a cylindrical coordinate system is reduced to solving the following equations [3]:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r \ \rho v) + \frac{\partial}{\partial z}(\rho w) = \dot{m}; \quad (2)$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v^2) + \frac{\partial}{\partial z}(\rho v w) = -\frac{\partial p}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r}(-r\rho\overline{v'^2}) + \quad (3)$$
$$+\frac{\partial}{\partial z}(-\rho\overline{v'w'}) - \rho s c_d v\sqrt{v^2+w^2};$$

$$\frac{\partial}{\partial t}(\rho w) + \frac{1}{r}\frac{\partial}{\partial r}(r \ \rho v w) + \frac{\partial}{\partial z}(\rho w^2) = -\frac{\partial p}{\partial z} + \quad (4)$$
$$+\frac{1}{r}\frac{\partial}{\partial r}(-r \ \rho\overline{v'w'}) + \frac{\partial}{\partial z}(-\rho\overline{w'^2}) - \rho s c_d w\sqrt{v^2+w^2} - \rho g;$$

$$\frac{\partial}{\partial t}(\rho c_p T) + \frac{1}{r}\frac{\partial}{\partial r}(r \ \rho v c_p T) + \frac{\partial}{\partial z}(\rho w c_p T) =$$
$$= \frac{1}{r}\frac{\partial}{\partial r}(-r\rho c_p\overline{v'T'}) + \frac{\partial}{\partial z}(-\rho c_p\overline{w'T'}) + k_g(cU_R - 4\sigma T^4) + \quad (5)$$
$$+ q_5 R_5 + \alpha_v(T_s - T);$$

$$\frac{\partial}{\partial t}(\rho c_\alpha) + \frac{1}{r}\frac{\partial}{\partial r}(r \ \rho v c_\alpha) + \frac{\partial}{\partial z}(\rho w c_\alpha) = \quad (6)$$
$$= \frac{1}{r}\frac{\partial}{\partial r}(-r\rho\overline{v'c'_\alpha}) + \frac{\partial}{\partial z}(-\rho\overline{w'c'_\alpha}) - R_{5\alpha}, \alpha = 1,2;$$

$$\frac{\partial}{\partial z}\left(\frac{c}{3k}\frac{\partial U_R}{\partial z}\right) - kcU_R + 4k_g\sigma T^4 + 4k_S\sigma T_s^4 = 0; \quad (7)$$

$$\sum_{i=1}^{4}\rho_i c_{pi}\varphi_i\frac{\partial T_s}{\partial t} = q_3 R_3 - q_2 R_2 + k_S(cU_R - 4\sigma T_s^4) + \quad (8)$$
$$+ \alpha_V(T - T_s);$$

$$\rho_1\frac{\partial \varphi_1}{\partial t} = -R_1, \rho_2\frac{\partial \varphi_2}{\partial t} = -R_2, \rho_3\frac{\partial \varphi_3}{\partial t} = \alpha_c R_1 - \frac{M_c}{M_1}R_3, \quad (9)$$
$$\rho_4\frac{\partial \varphi_4}{\partial t} = 0;$$

$$\sum_{\alpha=1}^{3} c_\alpha = 1, \ p_e = \rho RT\sum_{\alpha=1}^{3}\frac{c_\alpha}{M_\alpha},$$

$$\dot{m} = (1-\alpha_c)R_1 + R_2 + \frac{M_c}{M_1}R_3, R_{51} = -R_3 - \frac{M_1}{2M_2}R_5, \quad (10)$$
$$R_{52} = \nu(1-\alpha_c)R_1 - R_5;$$

$$R_1 = k_1\rho_1\varphi_1 \exp\left(-\frac{E_1}{RT_S}\right),\; R_2 = k_2\rho_2\varphi_2 T_S^{-0.5} \exp\left(-\frac{E_2}{RT_S}\right),$$

$$R_3 = k_3\rho\varphi_3 s_\sigma c_1 \exp\left(-\frac{E_3}{RT_S}\right),$$

$$R_5 = M_2 k_5 \left(\frac{c_1 M}{M_1}\right)^{0.25}\left(\frac{c_2 M}{M_2}\right) T^{-2.25} \exp\left(-\frac{E_5}{RT}\right).$$

The system of equations (1)–(10) must be solved taking into account the initial and boundary conditions:

$$t = 0{:}\, v = 0, w = 0, T = T_e, c_\alpha = c_{\alpha e}, T_s = T_e, \varphi_i = \varphi_{ie}; \quad (11)$$

$$r = 0{:}\, v = 0, \frac{\partial w}{\partial r} = 0, \frac{\partial T}{\partial r} = 0, \frac{\partial c_\alpha}{\partial r} = 0, \frac{\partial U_R}{\partial r} = 0; \quad (12)$$

$$r = r_e{:}\, \frac{\partial v}{\partial r} = 0, \frac{\partial w}{\partial r} = 0, \frac{\partial c_\alpha}{\partial r} = 0, \frac{\partial T}{\partial r} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial r} + \frac{c}{2}U_R = 0; \quad (13)$$

$$z = z_0{:}\, \frac{\partial v}{\partial z} = 0, \frac{\partial w}{\partial z} = 0, \frac{\partial T}{\partial z} = 0, \frac{\partial c_\alpha}{\partial z} = 0, {:} -\frac{c}{3k}\frac{\partial U_R}{\partial z} + \frac{c}{2}U_R = 0; \quad (14)$$

$$z = h{:}\, \frac{\partial v}{\partial z} = 0, \frac{\partial w}{\partial z} = 0, \frac{\partial T}{\partial z} = 0, \frac{\partial c_\alpha}{\partial z} = 0, \quad (15)$$

$$\frac{c}{3k}\frac{\partial U_R}{\partial z} + \frac{c}{2}U_R = 2q_R(r, z).$$

here and above v, w – velocity projection on the r axes and z; α_V is the coefficient of phase exchange; ρ - density of gas – dispersed phase, t is time; v_i - the velocity components; U_R - density of radiation energy, k - coefficient of radiation attenuation, P - pressure; c_p – constant pressure specific heat of the gas phase, c_{pi}, ρ_i, φ_i – 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_i – 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_e - the ambient temperature; R – universal gas constant; M_α , M_C, and M molecular mass of α -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 $\dot{m}$, outflow of oxygen R_{51}, changing carbon monoxide R_{52}. 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_i) are evaluated using data for mathematical model [3]. The initial values for volume of fractions of condensed phases are determined using the expressions:

$$\varphi_{1e} = \frac{d(1-\nu_z)}{\rho_1}, \varphi_{2e} = \frac{Wd}{\rho_2}, \varphi_{3e} = \frac{\alpha_c \varphi_{1e}\rho_1}{\rho_3}$$

where d -bulk density for surface layer, ν_z – 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)–(10), 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, [3]). The system of equations (1)–(10) contains terms associated with turbulent diffusion, thermal conduction, and convection, and needs to be closed. The components of the tensor of turbulent stresses $\rho\overline{v'w'}$, as well as the turbulent fluxes of heat and mass are written in terms of the gradients of the average flow properties. It should be noted that this system of equations describes processes of transfer within the entire region of the forest massif, which includes the space between the underlying surface and the base of the forest canopy, the forest canopy and the space above it, while the appropriate components of the data base are used to calculate the specific properties of the various forest strata and the near-ground layer of atmosphere. This approach substantially simplifies the technology of solving problems of predicting the state of the medium in the fire zone numerically. The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different (for example pine [3,4]) type of forest. The system of equations (1)–(10) must be solved taking into account the initial and boundary conditions (11)-(15).

III. The Numerical Solution and Results

The system of equations (1)-(10) with the appropriate initial and boundary conditions (11)-(15) described above for the numerical integration is reduced to discrete form using the control volume method [5]. Difference equations that arise in the course of sampling were resolved by the method of SIP [6]. Algorithm for solving the given problem involves splitting into physical processes, that is first calculated hydrodynamic pattern, and then solved the equations of chemical kinetics and chemical sources accounted for scalar functions. At the same time step for integrating the system of ordinary differential equations are automatically selected. Matching velocity and pressure fields was carried out iteratively as part of the algorithm SIMPLE [5].

On the basis of a mathematical model described numerical calculations were carried out to determine the pattern of occurrence of ignition process of forest cover due to the formation of the fireball and the effects of thermal radiation on the underlying surface. The result obtained by numerical integration of the field of mass concentrations of the components of the gas phase, the temperature, the volume fractions of the components of the solid phase. Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically. Fig. 2 illustrates the time dependence of dimensionless temperatures of gas and condensed phases, Fig. 3 – mass concentrations of gas components (1- oxygen, 2- gas products of pyrolysis), and Fig. 4 - relative volume fractions of solid phases, moisture and coke at high boundary of the forest. At the moment of ignition, the gas combustible products of pyrolysis burn 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 are of a gas - phase nature, i.e. initially heating of solid and gaseous phases occurs, moisture is evaporated. Then decomposition process into condensed and volatile pyrolysis products starts, the latter being ignited in the forest canopy.

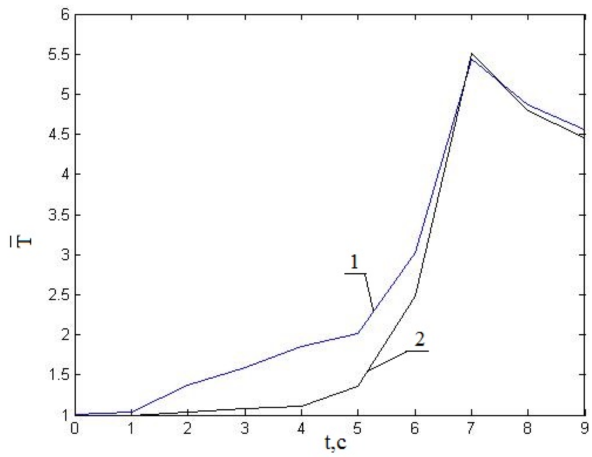

Fig. 2 temperature of condensed (1) and gas (2) phase: 2 - $\bar{T}$ **=*T*/*T*$_e$, 1 -** $\bar{T}_S$ **=*T*$_S$/*T*$_e$, *T*$_e$=3**00K

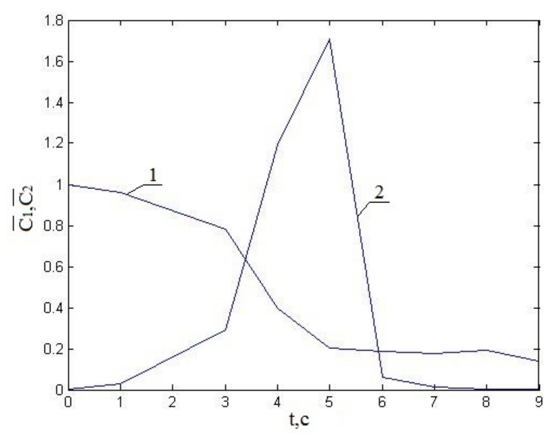

Fig. 3 The concentration of oxygen $\bar{c}_1$ (1) and gas products of pyrolysis $\bar{c}_2$ (2); $\bar{c}_\alpha = c_\alpha / c_{1e}$, $_{1e} = 0.23$.

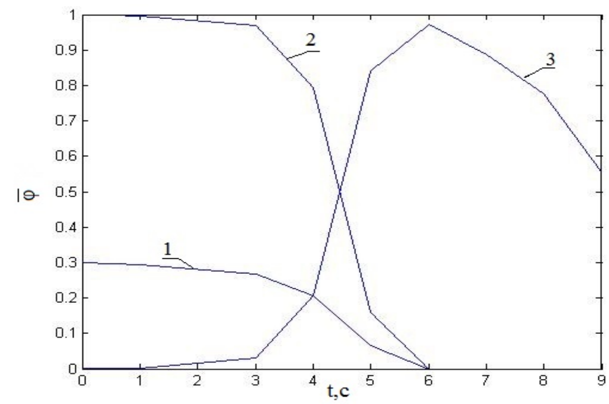

Fig. 4. volume fractions of solid phase:

$1 - \bar{\phi}_1 = \phi_1 / \phi_{1e}$, $2 - \bar{\phi}_2 = \rho_2 \phi_2 / \rho_c$, $3 - \bar{\phi}_3 = \rho_3 \phi_3 / \alpha_c \rho_1 \phi_{1e}$.

The model proposed there gives a detailed picture of the change in the velocity, temperature and component concentration fields with time in all domain and determine as well as the influence of different conditions on the crown forest fire spread. The distribution of isotherms of gas phase (Fig. 5): 1-3 correspond to the isotherms $\bar{T}$ = 1.5, 2., 2.6. Fig. 6 presents the distribution mass concentration of gas products of pyrolysis. In the vicinity of the source of heat and mass release, heated air masses and products of pyrolysis and combustion float up. On the basis of these data determined the values of the radii of the ignition of forests under the influence of the thermal radiation of the fireball, which depend on the moisture, content bulk of forest combustible materials and the mass of the spilled fuel. According to the data of calculation Figures 7-8 show these results. The radius of the ignition of vegetation maximum at a moisture content W = 0.2 and mass spilled flammable liquid m = 60 tons.

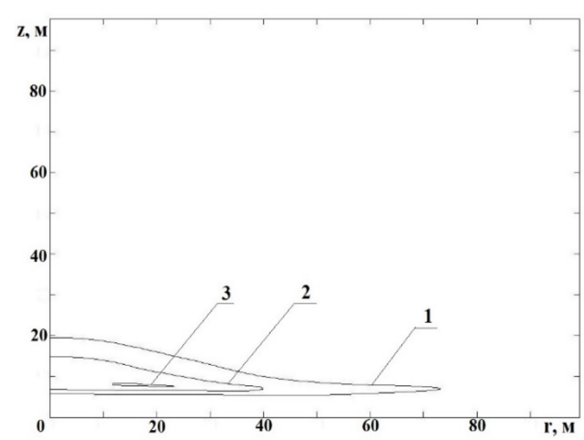

Fig. 5. The distribution of temperature of gas phase.

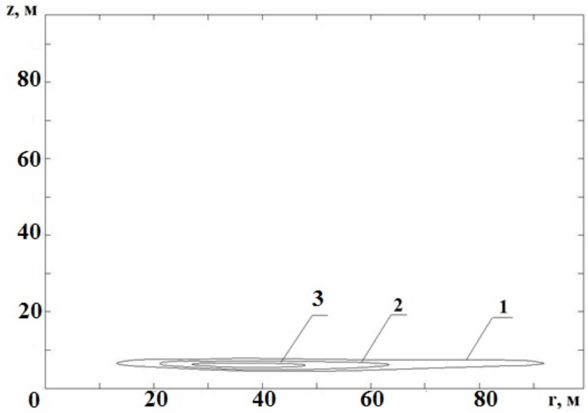

Fig. 6. The distribution of $\overline{c_2}$: 1 – 0.05; 2 – 0.07; 3 – 0.1.

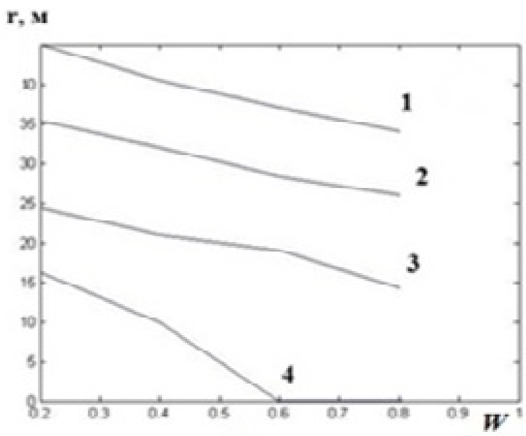

Fig. 7. The influence of moisture of forest combustible materials on the sizes of fires for different mass of spilled fuel: 1 – *m*= 60 tons, 2 – *m*= 40 tons, 3 – *m*= 20 tons, 4 – *m*= 10 tons.

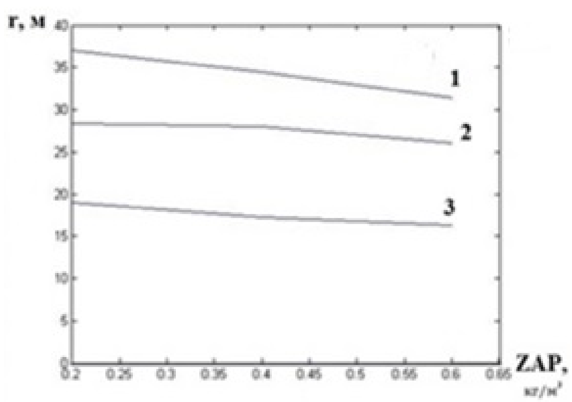

Fig. 8. The influence of bulk of forest combustible materials on the sizes of fires for different mass of spilled fuel: 1 – *m*= 60 tons, 2 – *m*= 40 tons, 3 – *m*= 20 tons, 4 – *m*= 10 tons.

With increasing moisture content of vegetation, the radius of ignition is decreased. The results of mathematical modeling of such phenomena can be used to develop preventive measures, as well as the liquidation of their consequences.

IV. Conclusion

1. On the basis of the theory of general mathematical model of forest fires [3] have developed a new mathematical model of ignition of forest as a result of emergency situations. It is taken into account turbulent flow, two-temperature environment and the main physical and chemical processes (drying and pyrolysis of forest fuels, chemical reaction of combustion of gaseous and condensed pyrolysis products afterburner.

2. Based on the finite volume method it is developed a method of numerical solution of unsteady two-dimensional equations of the theory of forest fires.

3. Analysis of the results of the numerical solution of the problem of forest massif ignition revealed that the following stages of the process: the heating of the canopy, the formation of gaseous pyrolysis products, their inflammation, the formation of gaseous products of pyrolysis of forest canopy and the ignition.

4. It was found that the radius of forest massif ignition decreases when moisture content of vegetation increases.

5. As a result of numerical calculations show that the ignition of forest fuel is a gas-phase nature.

References

[1] W.E. Martinsen, J.D. Marx, "An improved model for the prediction of radiant heat from fireball" in International Conference and Workshop on *Modeling consequences of Accidental Releases of Hazardous Materials*, San Francisco, September 28 – October 1, 1999.

[2] S.Glastone (Ed.), The Effects of Nuclear Weapons, U.S. Gov't. Printing Office, Washington, 1962.

[3] AM,Grishin, *Mathematical Modeling Forest Fire and New Methods Fighting Them*. Tomsk: Publishing House of Tomsk University, 1997.

[4] A.M.Grishin, V.A. Perminov, "An ignition of forest massifs under the influence of high altitude radiant energy", *Combustion, Explosion and Shock Waves*, vol. 32, no. 5, pp. 108-115, 1996.

[5] S.V.Patankar, *Numerical Heat Transfer and Fluid Flow*. New York: Hemisphere Publishing Corporation, 1981.

[6] H.L.Stone, "Iterative solution of implicit approximations of multidimensional partial differential equations", *SIAM Journal of Numerical Analysis*, no. 5, pp.530-558. 1968.

Valeriy A. Perminov is a professor of Department of Ecology and Basic Safety of Tomsk Polytechnic University. He was awarded a degree of doctor of physical and mathematical sciences in 2011. His career began at the Theory of forest fires Labs (Tomsk State University), where he gained valuable experience of mathematical modeling of forest fires and environmental pollution. These research themes have been very fruitful and highly collaborative, involving extensive interactions with Russian Foundation for Basic Research, International Science Foundation, Ministry of Forestry and etc. He has published over 150 academic papers and have written two text books. He is a member of Council on combustion and explosion of Siberian Department of Russian Academy of Science and American Chemical Society and the editorial team of the "International journal of GEOMATE" and the "Brain. broad research in artificial intelligence and neuroscience"**.** He has taken part in different all Russian and international conferences devoted to the problems of mathematical modeling of forest fires, environmental pollution and prediction of the ecological consequences of the natural and technogenic catastrophes.