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INFLUENCE OF THE WATER BARRIER ON THE DYNAMICS OF A FOREST FIRE CONSIDERING THE INHOMOGENEOUS TERRAIN AND TWO-TIER STRUCTURE OF THE FOREST

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ABSTRACT

This paper discusses issues related to the modeling of forest fire extinguishing. The mathematical formulation of the interaction of a forest fire with a water barrier is presented. The evolution of fire and vegetation structure influence on the processes of evaporation is demonstrated. It was concluded that use of water barrier in the presence of a dense layer of low vegetation is ineffective in stopping fire spread.

Keywords: forest fire, water barrier, fire extinguishing, simulation, free water.

INTRODUCTION

Analysis of the dynamics of large forest fires all over the world has shown disadvantages of existing methods of dealing with them. Successful fighting forest fires require adequate forecasting the dynamics of fire considering actions taken for its suppression.

There are many mathematical models of different levels devoting to forest fires. Empirical [**Error! Unknown switch argument.**] and semi empirical [**Error! Unknown switch argument.-Error! Unknown switch argument.**] models are based on a generalization of statistical and experimental data. There are several papers devoted to modeling firefighting based on semi-empirical models such as [[7]].

Physical models of forest fires [**Error! Unknown switch argument.**, **Error! Unknown switch argument.**] provide the detailed picture, based on the laws of mechanics reacting media, thus those models require a large amount of computation. Unlike empirical models physical models, allow to simulate detailed an interaction of fire with the water used to extinguish it, and find the most effective strategies for fighting the fire, based on the physical laws underlying the ongoing processes.

Extinguishing efficiency depends on the ability to supply sufficient quantity of water to the fire zone to moisten and cool forest fuels. Fire suppression scenario is largely determined by the ability of fire extinguishing equipment to deliver water to the burning target for the maximum possible distance. The initial size of the droplets in the water flow and the initial velocity are crucial to getting water in combustion zone. Modeling the droplet evaporation and flight trajectory discussed in [**Error! Unknown switch argument.**]. The paper [**Error! Unknown switch argument.**] devoted to investigation of shielding properties of the water curtain. Extinguishing fires in enclosed spaces and tunnels based on the using sprinkler systems discussed in [**Error! Unknown switch argument.**].

Dynamics of fire inside buildings and tunnels is significantly different from the fire dynamics in an open space. Thus during a forest fire distinct vertical convective flow takes place. The manuscript [**Error! Unknown switch argument.**] show that in case of water mist fire extinguishing from above 90-95% of water mist do not cause the desired effect.

Despite the large number of papers the problem of extinguishing a forest fire has not solved using a full model considering physical and chemical processes, and aerodynamics. Among the existing methods of extinguishing forest fires the following approaches should be highlighted: water discharge from above, the water supply to the fire area by terrestrial means and creating a water barrier. Existing rules of forest fire extinguishing usually based on engineering methods of calculating the required amount of water and observations. Recent years' experience in fighting large fires has shown that their dynamics often goes beyond forecasts, and it leads to disastrous consequences. Therefore, the problem of numerical simulation of forest fires considering the key physical, chemical and hydrodynamic processes remains an important and relevant.

The aim of this study is investigation the influence of the density of forest fuel and terrain on the effectiveness of the water barrier.

METHODS

Dynamics of forest fire depends on the density distribution of combustible material and topography. This paper examines two variants of forest structure: one-level and two-level. In both cases, the forest height is 4 m One-level forest is modeled as a homogeneous combustible medium having density of 2kg/m^{3}over the entire height. Two-level forest have bottom layer litter, dry grass and

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small shrubs containing with height of 40 cm and fuel density of 8 kg/m^3. Upper layer of two-level forest have height of 3.6 m and density of 2 kg/m^3.Thereisnobreakintwo-levellayer. Physical model of the problem is shown in Figure-1. Figure-1 (a) shows the geometry of the problem in the case of fire spread on the hill terrain. The structure of two-level forest was demonstrated on Figure-1 (b). Water barrier and topography are also shown in the results in Section 3. It is assumed that the moisture barrier has a width of 40 cm and the height of 4 m, which corresponds to the height of the forest.

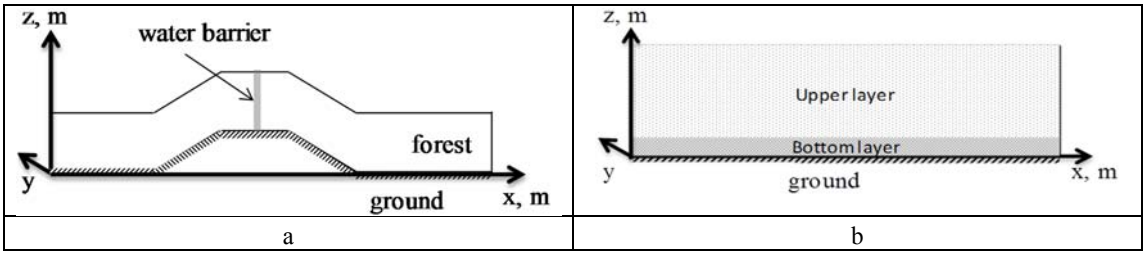

Figure-1. Geometry of model.

Water is one of the most common means of fighting forest fires. The vigorous boiling occurs when it enters the combustion zone, which leads to the absorption of thermal energy and release of water vapor. It is assumed that at temperatures above the boiling point of water the whole supplied energy is spent to the process of boiling and the temperature of the fluid itself remains almost constant. Thus, it is not possible for the boiling process to define the mass velocity as a function of water temperature, as it is defined for other physical and chemical processes [[14]].

We assume that the free water reserve can be consumed by boiling and replenished, for example, as a result of using water cannons in a given region.

$$\rho_4 \frac{\partial \varphi_4}{\partial t} = -R_4 + f(x,z,t). \tag{1}$$

According to the physical model of forest fires, which does not consider the process of boiling of free water, temperature is determined from

$$\frac{\partial\left(\left(\sum_{i=1}^{4}\rho_i\varphi_i c_{pi} + \rho_5 c_{p5}\right)T\right)}{\partial t} + \frac{\partial\left(\rho_5 c_{p5} UT\right)}{\partial x} + \frac{\partial\left(\rho_5 c_{p5} WT\right)}{\partial z} = \\ = \frac{\partial}{\partial x}\left(\lambda_t \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(\lambda_t \frac{\partial T}{\partial z}\right) - q_2 R_2 + q_3 R_3 + q_5 R_5 + k_s\left(cU_R - 4\sigma(T^4 - T_e^4)\right). \tag{2}$$

After simple transformations and substitution of $\frac{\partial T}{\partial t} = T'$, the equation (2) will take the form

$$T'\left(\sum_{i=1}^{4}\rho_i\varphi_i c_{pi} + \rho_5 c_{p5}\right) + T\frac{\partial}{\partial t}\left(\sum_{i=1}^{4}\rho_i\varphi_i c_{pi} + \rho_5 c_{p5}\right) + \frac{\partial\left(\rho_5 c_{p5} UT\right)}{\partial x} + \frac{\partial\left(\rho_5 c_{p5} WT\right)}{\partial z} = \\ = \frac{\partial}{\partial x}\left(\lambda_t \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(\lambda_t \frac{\partial T}{\partial z}\right) - q_2 R_2 + q_3 R_3 + q_5 R_5 + k_s\left(cU_R - 4\sigma(T^4 - T_e^4)\right). \tag{3}$$

In the equation (3) value of T' determines the rate of change of temperature in the case of absence of vaporization process. Water boils provided that its temperature is not lower than the boiling point and has enough energy for maintaining the process. Thus, theoretically, the following cases are possible:

a) There is a non-zero water supply, mass flow rate of boiling is limited by energy flux density and temperature remains at the level of T_b. In this case boiling rate is determined by

$$R_4 = \frac{1}{q_4} T'\left(\sum_{i=1}^{4}\rho_i\varphi_i c_{pi} + \rho_5 c_{p5}\right). \tag{4}$$

b) Temperature is above the boiling point, all incoming water is evaporated. In this case the boiling rate may be expressed as

$$R_4 = f(x,z,t). \tag{5}$$

c) If the temperature is below the boiling point $T < T_b$ or there is no free water, then boiling process does not occur.

$$R_4 = 0. \tag{6}$$

This model does not consider the case of abrupt increases in temperature or concentration, because in this

case the rate of boiling in model would be reduced to a delta function. Unlike [[15]], this article uses an improved form of free water boiling rate calculation.

$$\frac{\partial\left(\left(\sum_{i=1}^{4}\rho_i\varphi_i c_{pi}+\rho_5 c_{p5}\right)T\right)}{\partial t}+\frac{\partial\left(\rho_5 c_{p5}UT\right)}{\partial x}+\frac{\partial\left(\rho_5 c_{p5}WT\right)}{\partial z}= \tag{7}$$
$$=\frac{\partial}{\partial x}\left(\lambda_t\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial z}\left(\lambda_t\frac{\partial T}{\partial z}\right)+q_1R_1-q_2R_2+q_3R_3-q_4R_4+q_5R_5+k_s\left(cU_R-4\sigma\left(T^4-T_e^4\right)\right).$$

$$Q=\left(1-\alpha_c\right)R_1+R_2+R_4+\frac{M_c}{M_1}R_3 \tag{8}$$

In order to determine the initial volume fraction of water in the barrier the following equation is used:

$$\varphi_{4b}=\varphi_1\frac{\rho_1}{\rho_4}w_b\,, \tag{9}$$

According to the model above, process of replenishment and consumption of water to the boiling during forest fire is simulated. In this work assumed that there is a water barrier representing area containing free water that after heating to a boiling temperature uses all the energy supplied to it for the vaporization process. At the beginning of the calculation density of barrier is determined by the mass fraction of water inside. Specific density values are given in the respective calculations.

THEORY AND CALCULATION

Method of large particles [[16]] for the staggered pattern considering splitting both processes, and the spatial coordinates [[17]] used to solve the problem.

Advantages of the method of large particles are its stability and simplicity in implementation. The disadvantages of this method are the first order of accuracy and significant artificial viscosity. Using the staggered pattern allowed to simulate the corner points associated with the in homogeneities of relief. Scheme of pattern is shown in Figure-2. In the center are determined the quantities relating to the corresponding cell.

The equations (7) - (8) should be introduced in order to simulate addition free water phase.

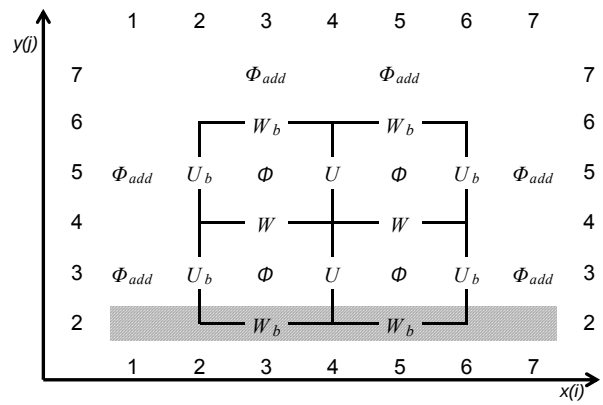

Figure-2. Scheme of the staggered pattern.

RESULTS AND DISCUSSIONS

According to the model presented above the interaction of fire with water barrier was simulated.

Temperature on **Figure-3.1-3.2** is shown as a gray-scale color; arrows represent the velocity field; water barrier is shown as a solid black area, which thickness corresponds to the distribution of the proportion of water remaining in the barrier along the entire height of forest.

Figure-3.1 shows dynamics of fire in one-level forest at the moment of combustion front collision with a barrier. Density of barrier is 1.6 kg/m^3 in the case of plain terrain and 2.5 kg/m^3 in the case of hill. It can be clearly seen that fire comes to barrier slightly faster in the case heterogeneous relief.

It can be seen from the calculation results, that in the propagation of fire across the plain, the front of the fire is restored after passing the barrier, but the bottom layer is not involved in the process. When spreading along the hill fire is not able to re-gain fire rate until it reaches leeward slope, because fire is directed primarily horizontally in the hearth and the bulk of the heated mass go out of the forest canopy. In case of fire spread across the plain at time 7.6 seconds can be seen that the barrier is almost not affected. At the time of 8 seconds, it can be seen that the temperature in the combustion zone is substantially decreased and the barrier partially boiled off. Once the barrier has ceased to exist, the fire front gained temperature again at time of 8.4 seconds. However barrier prevented heat propagation, so moisture inside the forest fuel did not evaporate. Therefore fire propagation would

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need extra energy to evaporate moisture. Lack of energy led to the cessation of fire.

In the right column of **Figure-3.1** one can see the collision dynamics of fire with a water barrier on the plateau of the hill. The greater slope is typical for the fire on the plateau comparing to the plain, resulting that in 8.4 seconds barrier is not completely boiled away. Despite the fact that the energy of the fire is enough to vaporize all of its water, the fire will also cease.

Figure-3.2 shows the evolution of forest fire spreading through hill and plains, respectively, in the two-level forest. Moisture barrier have density 20 kg/m^3 in this case. At the initial stage of fire a pattern of spreading is approximately the same and does not depend of the terrain. At time of 10 seconds in both cases, the heated gas streams flow past the barrier and almost do not evaporate it. During fire spread on the windward slope the speed of the upper front is increased. At the moment of 14 seconds fire reaches barrier in the case of spreading on plain, which leads to the power consumption on its evaporation in the upper front.

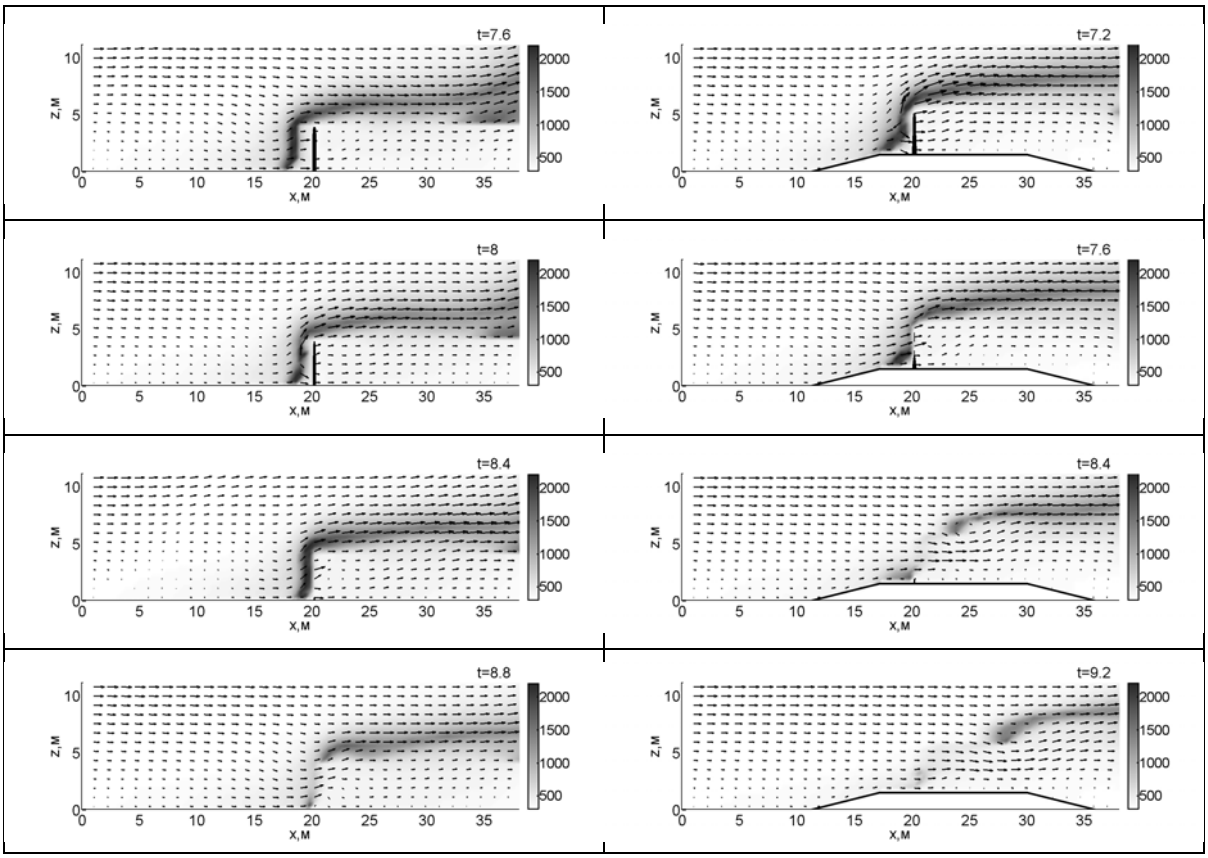

Figure-3. Dynamics of forest fire in one-level forest when spreading through a water barrier on the relief of various configurations.

Numerical simulation results showed that the combined action of convective effects and external velocity field makes the lower part of the barriers to evaporate weakly, what leads to the cessation of burning in lower dense layer.

There is a similar effect when considering fire spreading on a plateau of hill, although somewhat later due to the position of the barrier. In both cases the lower edge of the fire is behind the upper one due to the higher density of materials and lower wind speed. Consequently, almost the entire heated gas stream is directed to water barrier. At the moment of 22 seconds hot gas flows are shown when water barrier is evaporating. At this point, the active combustion zone is located about 2-4 meters from the barrier that provides sufficient time to overcome it.

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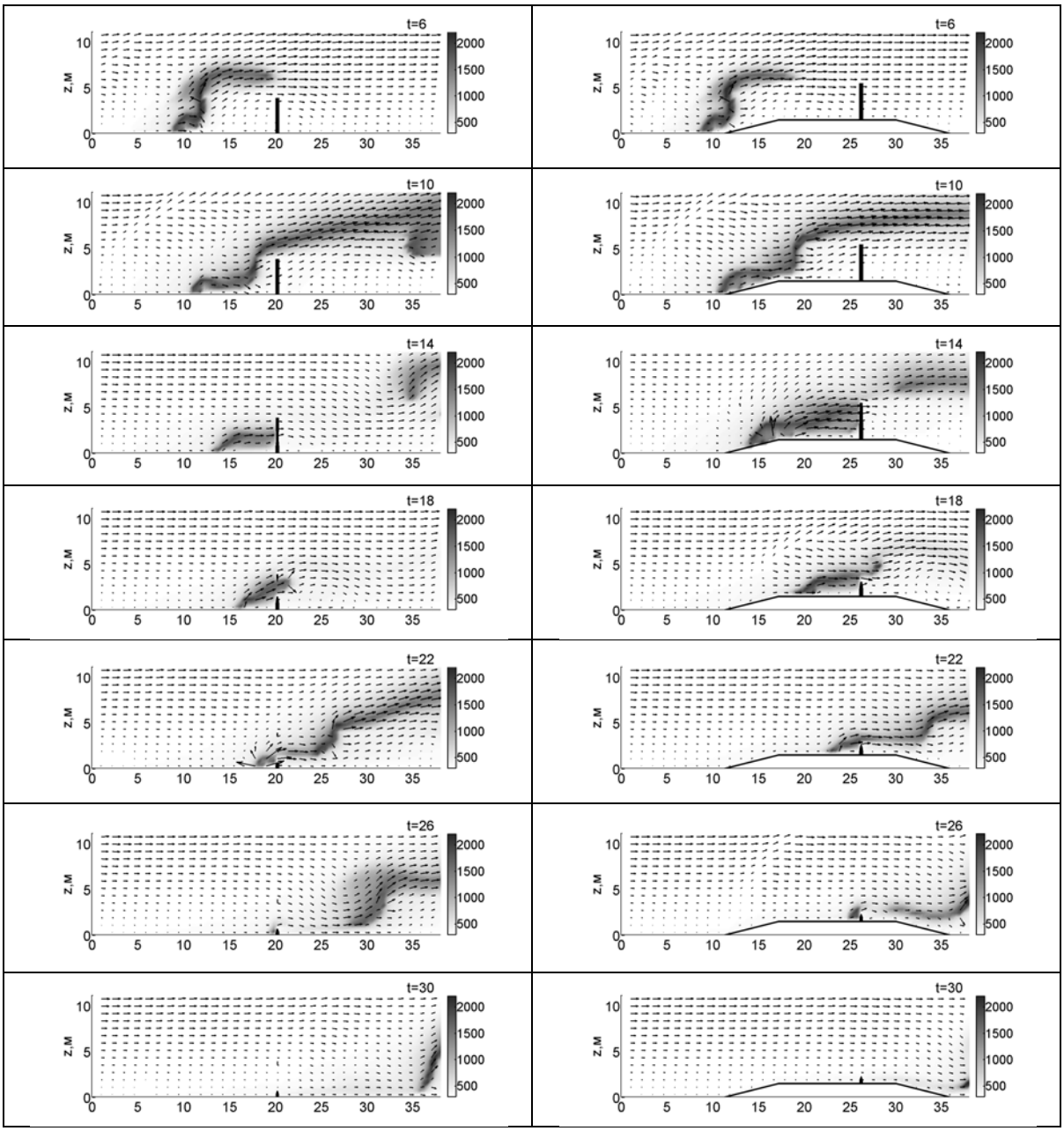

Figure-4. Dynamics of a forest fire in the two-level forest when spreading through a water barrier on the relief of

various configurations.

CONCLUSIONS

The presented results demonstrate that in the case of two-level forest fuel the convective gas flows from the combustion hearth in the bottom layer are directed to water barrier, which leads to its boiling off. As a result, the fire extinguishing with water barrier becomes ineffective. This effect is not observed in the case of one-level forest. Bottom layer has greater impact on efficiency of water barrier than the hill.

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APPENDIX A. MATHEMATICAL MODEL OF FOREST FIRE AND WATER BARRIER INTERACTION

Complete mathematical model for the case of forest fires extinguish using water barrier has the form:
Equation of continuity of the gas phase

$$\frac{\partial\left(\left(\sum_{i=1}^{4}\rho_i\varphi_i c_{pi}+\rho_5 c_{p5}\right)T\right)}{\partial t}+\frac{\partial\left(\rho_5 c_{p5}UT\right)}{\partial x}+\frac{\partial\left(\rho_5 c_{p5}WT\right)}{\partial y}= \\ =\frac{\partial}{\partial x}\left(\lambda_t\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_t\frac{\partial T}{\partial y}\right)-q_2R_2+q_3R_3-q_4R_4+q_5R_5+k_s\left(cU_R-4\sigma(T^4-T_e^4)\right), \quad (13)$$

equation of conservation of the gas phase components

$$\frac{\partial\left(\rho_5 C_\alpha\right)}{\partial t}+\frac{\partial\left(\rho_5 C_\alpha U\right)}{\partial x}+\frac{\partial\left(\rho_5 C_\alpha W\right)}{\partial z}= \\ =\frac{\partial}{\partial x}\left(\rho_5 D_t\frac{\partial C_\alpha}{\partial x}\right)+\frac{\partial}{\partial z}\left(\rho_5 D_t\frac{\partial C_\alpha}{\partial z}\right)+R_{5\alpha},\ \alpha=\overline{1,2}, \quad (14)$$

equation of state of gas phase

$$P=\frac{\rho_5 RT}{M},\ \frac{1}{M}=\sum_{\alpha=1}^{3}\frac{C_\alpha}{M_\alpha},\ \sum_{\alpha=1}^{3}C_\alpha=1, \quad (15)$$

equation of radiant energy transfer - differential model

$$\frac{\partial}{\partial x}\left(\frac{c}{3k_\Sigma}\frac{\partial U_R}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{c}{3k_\Sigma}\frac{\partial U_R}{\partial z}\right)-k_s\left(cU_R-4\sigma(T^4-T_e^4)\right)=0, \quad (16)$$

equations of conservation of the volume fractions of components of the condensed phase

$$\rho_1\frac{\partial\varphi_1}{\partial t}=-R_1,\ \rho_2\frac{\partial\varphi_2}{\partial t}=-R_2,\ \rho_3\frac{\partial\varphi_3}{\partial t}=\alpha_c R_1-\frac{M_c}{M_1}R_3,\ \rho_4\frac{\partial\varphi_4}{\partial t}=-R_4, \quad (17)$$

the volume fraction of the gas phase is determined according to relation

$$\varphi_5=1-\sum_{i=1}^{4}\varphi_i, \quad (18)$$

mass rate of formation of the gas phase

$$Q=\left(1-\alpha_c\right)R_1+R_2+\frac{M_c}{M_1}R_3+R_4, \quad (19)$$

mass flow rate of the pyrolysis of forest fuel

$$R_1=k_1\rho_1\varphi_1\exp\left(-\frac{E_1}{RT}\right), \quad (20)$$

mass flow rate of the moisture evaporation present in the forest combustible materials

$$\frac{\partial\rho_5}{\partial t}+\frac{\partial\left(\rho_5 U\right)}{\partial x}+\frac{\partial\left(\rho_5 W\right)}{\partial z}=Q, \quad (10)$$

conservation of momentum equation for the velocity components

$$\frac{\partial\left(\rho_5 U\right)}{\partial t}+\frac{\partial\left(\rho_5 U^2\right)}{\partial x}+\frac{\partial\left(\rho_5 UW\right)}{\partial z}=-\frac{\partial P}{\partial x}- \\ -\rho_5 Sc_d U\sqrt{U^2+W^2}+\frac{\partial}{\partial x}\left(\mu_t\frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu_t\frac{\partial U}{\partial z}\right), \quad (11)$$

$$\frac{\partial\left(\rho_5 W\right)}{\partial t}+\frac{\partial\left(\rho_5 UW\right)}{\partial x}+\frac{\partial\left(\rho_5 W^2\right)}{\partial z}=-\frac{\partial P}{\partial z}- \\ -\rho_5 Sc_d W\sqrt{U^2+W^2}+\frac{\partial}{\partial x}\left(\mu_t\frac{\partial W}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu_t\frac{\partial W}{\partial z}\right)-\rho_5 g, \quad (12)$$

energy conservation equation

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$$R_2 = k_2\rho_2\varphi_2 T^{-0.5}\exp\left(-\frac{E_2}{RT}\right), \quad (21)$$

mass flow rate of thecombustion of condensed products of pyrolysis

$$R_3 = k_3 S_\sigma \rho_5 \varphi_3 C_1 \exp\left(-\frac{E_3}{RT}\right), \quad (22)$$

Mass flow rate of combustion of volatile pyrolysis products

$$R_5 = \begin{cases} k_5 M_2 T^{-2.25}\exp\left(-\frac{E_5}{RT}\right)x_1^{0.25}x_2,\ x_1 \ge 0.05, \\ k_5 M_2 T^{-2.25}\exp\left(-\frac{E_5}{RT}\right)x_1 x_2,\ x_1 < 0.05, \end{cases}, \quad (23)$$

$$x_i = \frac{C_i}{\sum_{k=1}^{3}\frac{C_k}{M_k}M_i},$$

mass rate of gas phase components formation

$$R_{51} = -R_3 - \frac{R_5 M_1}{2M_2},\ R_{52} = (1-\alpha_c)\nu_\Gamma R_1 - R_5, \quad (24)$$

Value of R_4 should be obtained from (4)-(6) respecting corresponding conditions.

To close the system at the boundary corresponding to the surface of the earth used impermeability and sticking conditions for gas phase velocity. We assume that the solid surface does not conduct heat. Free transfer conditions were setat the side and upper boundariesof the computational domain. The gas phase velocity at side and upper boundaries is determined on the basis of a given profile, taking into account wave attenuation passing through the borders. Concentrations of the components of the gas phase and the temperature as well as density of the heat radiant flux at the free boundaries are assumed to be equal to the values in the ambient media. Boundary conditions, based on above assumptions made have following form

$$z = h_{\max} : T = T_e, U = U_e, W = \frac{P-P_e}{P}\sqrt{\frac{RT}{M}}, C_\alpha = C_{\alpha e}, \alpha = \overline{1,2}, U_R = U_{\mathrm{Re}}, \quad (25)$$

$$x = 0 : T = T_e, U = \frac{z}{h_{\max}}U_e - \frac{P-P_e}{P}\sqrt{\frac{RT}{M}}, W = 0, C_\alpha = C_{\alpha e}, \alpha = \overline{1,2}, U_R = U_{\mathrm{Re}}, \quad (26)$$

$$x = x_{\max} : T = T_e, U = \frac{z}{h_{\max}}U_e + \frac{P-P_e}{P}\sqrt{\frac{RT}{M}}, \quad (27)$$
$$W = 0, C_\alpha = C_{\alpha e}, \alpha = \overline{1,2}, U_R = U_{\mathrm{Re}},$$

$$G : D_t = 0,\ \mu_t = 0,\ \lambda_t = 0,\ U = 0,\ W = 0,\ \frac{\partial U_R}{\partial \overline{n}} = 0, \quad (28)$$

where G - solid boundary corresponding to the ground surface; index $\overline{n}$ - the unit vector normal to the surface

At the initial time temperature, radiant energy flux density and concentration of the gas components are equal to the corresponding values in the ambient media. Velocity is defined as a linear profile..

$$T = T_e,\ U = \frac{z}{h_{\max}}U_e,\ W = 0,\ C_\alpha = C_{\alpha e},\ \alpha = \overline{1,2},\ U_R = U_{\mathrm{Re}}. \quad (29)$$

In the forest canopy within the value volume fractions of the canopy is defined by $\varphi_\alpha = \varphi_{\alpha e}, \alpha = \overline{1,3}$; there is no condensed fractions outside forest layer $\varphi_\alpha = 0,\ \alpha = \overline{1,3}$. Seat of the fire is defined in the form of a square with sides of 2 meters, where temperature maintained not below 1200 K for 1 s.

In the case of inhomogeneous terrain velocity field calculation performed before fire modelling.

APPENDIX B. SYMBOLS AND VALUES OF PARAMETERS

$\rho_i, c_{pi}, \varphi_i$ – density, kg/m^3, volume fraction and specific heat capacity respectively, J/(kg*K), *i-th* phase; (*i*=1 - forest fuel, *i*=2 - moisture, *i*=3 - condensed products of pyrolysis, *i*=5 - gas phase); T – temperature, K; C_α - mass concentrations of gas phase components (*i*=1 – oxygen, *i*=2 - volatile pyrolysis products, *i*=3 - non-reacting components of gas phase including steam); *U, W* - horizontal and vertical velocity components of the gas phase, m/s; P - pressure, Pa; U_R – radiation flux density, J/m^4; k_Σ - attenuation coefficient, s^{-2}; k_s - spectral absorption coefficient; c – speed of light, m/s; σ - Stefan-Boltzmann constant, kg·s^{-3}·K^{-4}; q_i, R_i - specific heat effect and the mass flow rate of chemical-physical processes respectively (*i*=1 - pyrolysis of forest fuel, *i*=2 - evaporation of moisture present in the forest combustible materials, *i*=3 - combustion of condensed products of pyrolysis, *i*=4 - boiling of free water, *i*=5 – combustion of

volatile pyrolysis products)J/kg, kg/(s·m^3); Q – is source of mass in gas phase as a result of chemical-physical process, kg/(s·m^3); M_α, M_c, M - molar masses of the individual components, carbon, and the whole mixture, kg/mol; S - specific surface canopy phytomass, 1/m; c_d - empirical drag coefficient; α_c, ν_Γ - coke number of forest fuel and the mass fraction of combustible gas in the total mass of volatile pyrolysis products, respectively; μ_t, λ_t, D_t - coefficients of dynamic viscosity, thermal conductivity and turbulent diffusion, Pa·s,W/(m·K), m^2/s; E_iиk_i - activation energy and pre-exponential factor of*i-th* chemical-physical process (i=1 - pyrolysis of forest fuel, i=2 - evaporation of moisture present in the forest combustible materials, i=3 - combustion of condensed products of pyrolysis, i=4 - boiling of free water, i=5 - combustion of volatile pyrolysis products); w_b - - the ratio of mass of water to mass of forest fuel in the barrier; g -- gravity, m/s^2; $T_b \approx 373\ K$ - boiling point of free water; $f(x,z,t)$ - water flow rate, kg/(m^3·s), subscript $_e$ related to ambient media.

Parameters used in simulations

T_e= 300 K; E_1 = 9400RK; E_2 = 6000RK; E_3 = 10000RK; E_5 = 11500RK; k_1 = 36300 c^{-1}; k_2 = 600000 K^{0,5}·c^{-1}; k_3 = 1000 kg·c^{-1}/m^2; k_5 = 3·10^{13} K^{2,25}·моль·c^{-1}/m^3 ; ρ_1 = 360 kg/m^3; ρ_3 = 200 kg/m^3; q_2 = 3·10^{6}J/kg; q_3 = 1,2·10^{7}J/kg; q_4 = 2,26·10^{6}J/kg; q_5 = 1·10^{7}J/kg; T_e = 300 K; C_{1e} =0,23143;c_{p1} = 2000 J/(kg·K);c_{p2} = 4180 J/(kg·K);c_{p3} = 900 J/(kg·K);c_{p4} = 4200 J/(kg·K).