A numerical study of thermal impact of forest fires on buildings

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Abstract

The mathematical modeling of forest fires actions on buildings and structures have been carried out to study the effects of fire intensity and wind speed on possibility of ignition of buildings. The crown forest fire is introduced as a heat and mass source defined by the empirical values of average crown fire temperature and vertical gas velocity at the top crown surface dependent on fire intensity. The hydrodynamic and thermal interactions between plume, wind flow and building are analyzed. The approach to modeling is based on the use of standard non-stationary three-dimensional conservation equations for turbulent flow in a multiphase reacting medium that are solved numerically under the input conditions characteristic of a large forest fires.

Keywords: **Computation Control volume, Crown fire, Fire spread, Forest fire, Mathematical model, Ignition, Building**

Introduction

The protection of buildings and structures in a community from destruction by fire is a very important concern. This paper addresses the development of a mathematical model for impact of wildfires with buildings. The forest fire is a very complicated phenomenon. At present, fire services can forecast the danger rating of, or the specific weather elements relating to, forest fire. There is need to understand and predict forest fire initiation, behavior and impact of fire on the buildings and constructions. This paper's purposes are the improvement of knowledge on the fundamental physical mechanisms that control forest fire behavior. A great deal of work has been done on the theoretical problem of forest fires. The first accepted method for prediction of crown fires was given by Rothermal [1] and Van Wagner [2]. The semi-empirical models [1-2] allow to obtain a quite good data of the forest fire rate of spread as a function of fuel bulk and moisture, wind velocity and the terrain slope. But these models use data for particular cases and do not give results for general fire conditions. Also crown fires initiation and hazard have been studied and modeled in detail (eg: Alexander [3], Xanthopoulos, [4], Van Wagner, [5], Cruz [6], Albini [7], Scott, J. H. and Reinhardt, E. D. [8]. The discussion of the problem of modeling forest fires is provided by Grishin [9]. A mathematical model of forest fires was obtained by Grishin [9] based on an analysis of known and original experimental data and using concepts and methods from reactive media mechanics. The physical two-phase models used in [10] may be considered as a development and extension of the formulation proposed by Grishin [9]. However, the study of crown fires initiation and spread [9,10] has been limited mainly to cases studied of forest fires propagation without take into account the mutual interaction of crown forest fires with different obstacles (roads, glades and etc.), buildings and constructions. In this paper, the impacts of crown forest fires on buildings are studied. The dangerous distances between forest and buildings are calculated in cases when the buildings will be ignited under the influence of forest fires.

1. Physical and mathematical model

It is assumed that the forest during a fire can be modeled as 1) 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 point x_1, x_2 , x_3= 0 is situated at the center of the surface forest fire source at the height of the roughness level, axis $0x_1$ directed parallel to the Earth's surface to the right in the direction of the unperturbed wind speed, axis $0x_2$ directed perpendicular to $0x_1$ and axis $0x_3$ directed upward (Fig. 1). The building is situated on the right part of the picture.

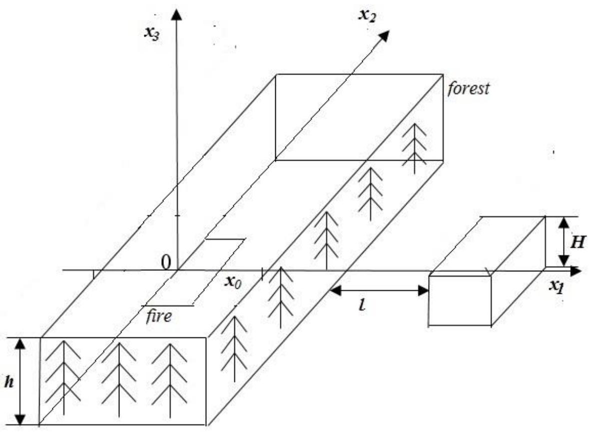

Figure 1. The scheme of calculation domain.

The problem formulated above reduces to the solution of the next system of equations:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho v_j)=Q,\ j=\overline{1,3},\ i=\overline{1,3}; \tag{1}$$

$$\rho\frac{dv_i}{dt}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}(-\rho\overline{v_i'v_j'})-\rho s c_d v_i\,|\vec{v}\,|-\rho g_i-Qv_i; \tag{2}$$

$$\rho c_p\frac{dT}{dt}=\frac{\partial}{\partial x_j}(-\rho c_p\overline{v_j'T'})+q_5R_5-\alpha_v(T-T_s)+k_g(cU_R-4\sigma T^4); \tag{3}$$

$$\rho\frac{dc_\alpha}{dt}=\frac{\partial}{\partial x_j}(-\rho\overline{v_j'c_\alpha'})+R_{5\alpha}-Qc_\alpha,\ \alpha=1,2; \tag{4}$$

$$\frac{\partial}{\partial x_j}\left(\frac{c}{3k}\frac{\partial U_R}{\partial x_j}\right)-kcU_R+4k_S\sigma T_S^4+4k_g\sigma T^4=0, \quad (5)$$

$$k=k_g+k_S;$$

$$\sum_{i=1}^{4}\rho_i c_{pi}\varphi_i\frac{\partial T_S}{\partial t}==q_3R_3-q_2R_2-k_S(cU_R-4\sigma T_S^4)+\alpha_v(T-T_S); \quad (6)$$

$$\rho_1\frac{\partial\varphi_1}{\partial t}=-R_{1s},\rho_2\frac{\partial\varphi_2}{\partial t}=-R_{2s},\rho_3\frac{\partial\varphi_3}{\partial t}=\alpha_C R_{1s}-\frac{M_C}{M_1}R_{3w},\rho_4\frac{\partial\varphi_4}{\partial t}=0; \quad (7)$$

$$\sum_{\alpha=1}^{3}c_\alpha=1,\ P_e=\rho RT\sum_{\alpha=1}^{3}\frac{c_\alpha}{M_\alpha},\ \vec{v}=(v_1,v_2,v_3),\ \vec{g}=(0,0,g).$$

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

$$t=0: v_1=0, v_2=0, v_3=0, T=T_e, c_\alpha=c_{\alpha e}, T_s=T_{se}, \varphi_i=\varphi_{ie}; \quad (8)$$

$$x_1=0: v_1=V, v_2=0, v_3=0, T=T_e, c_\alpha=c_{\alpha e}, -\frac{c}{3k}\frac{\partial U_R}{\partial x_1}+\frac{c}{2}U_R=0; \quad (9)$$

$$x_1=x_{1e}: \frac{\partial v_1}{\partial x_1}=0, \frac{\partial v_2}{\partial x_1}=0, \frac{\partial v_3}{\partial x_1}=0, \frac{\partial T}{\partial x_1}=0, \ \frac{\partial c_\alpha}{\partial x_1}=0, \frac{c}{3k}\frac{\partial U_R}{\partial x_1}+\frac{c}{2}U_R=0; \quad (10)$$

$$x_2=-x_{2e}: \frac{\partial v_1}{\partial x_2}=0, \frac{\partial v_2}{\partial x_2}=0, \frac{\partial v_3}{\partial x_2}=0, \frac{\partial T}{\partial x_2}=0, \ \frac{\partial c_\alpha}{\partial x_2}=0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_2}+\frac{c}{2}U_R=0; \quad (11)$$

$$x_2=x_{2e}: \frac{\partial v_1}{\partial x_2}=0, \frac{\partial v_2}{\partial x_2}=0, \frac{\partial v_3}{\partial x_2}=0, \frac{\partial T}{\partial x_2}=0, \ \frac{\partial c_\alpha}{\partial x_2}=0, \frac{c}{3k}\frac{\partial U_R}{\partial x_2}+\frac{c}{2}U_R=0; \quad (12)$$

$$x_3=0: \ v_1=0, v_2=0, \frac{\partial c_\alpha}{\partial x_3}=0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_3}+\frac{c}{2}U_R=0,$$
$$\rho v_3=\rho_0\omega_0, T=T_0, |x_1|\le x_0, |x_2|\le x_0, \quad (13)$$
$$\rho v_3=0, T=T_e, |x_1|>x_0, |x_2|>x_0;$$

$$x_3=x_{3e}: \frac{\partial v_1}{\partial x_3}=0, \frac{\partial v_2}{\partial x_3}=0, \frac{\partial v_3}{\partial x_3}=0, \frac{\partial T}{\partial x_3}=0, \ \frac{\partial c_\alpha}{\partial x_3}=0, \frac{c}{3k}\frac{\partial U_R}{\partial x_3}+\frac{c}{2}U_R=0. \quad (14)$$

Here and above $\frac{\mathrm{d}}{\mathrm{d}t}$ is the symbol of the total (substantial) derivative; α_V is the coefficient of phase exchange; ρ - density of gas – dispersed phase, t is time; v_i - the velocity components; T, T_S, - temperatures of gas and solid phases, 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; c_α - mass concentrations of α - component of gas - dispersed medium, index α=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_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 Q, outflow of oxygen R_{51}, changing carbon monoxide R_{52}.

$$Q = (1-\alpha_c)R_1 + R_2 + \frac{M_c}{M_1}R_3, R_{51} = -R_3 - \frac{M_1}{2M_2}R_5,$$
$$R_{52} = \nu_g(1-\alpha_c)R_1 - R_5, R_{53} = 0.$$

$$R_1 = k_1\rho_1\varphi_1 \exp\left(-\frac{E_1}{RT_s}\right), R_2 = k_2\rho_2\varphi_2 T_s^{-0.5}\exp\left(-\frac{E_2}{RT_s}\right),$$
$$R_3 = k_3\rho\varphi_3 s_\sigma c_1 \exp\left(-\frac{E_3}{RT_s}\right), R_5 = k_5 M_2\left(\frac{c_1 M}{M_1}\right)^{0.25}\frac{c_2 M}{M_2}T^{-2.25}\exp\left(-\frac{E_5}{RT}\right).$$

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)–(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 $\rho\overline{v_i'v_j'}$, as well as the turbulent fluxes of heat and mass $\overline{\rho v_j' c_p T'}$, $\overline{\rho v_j' c_\alpha'}$ are written in terms of the gradients of the average flow properties using the formulas

$$-\rho\overline{v_i v_j} = \mu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) - \frac{2}{3}K\delta_{ij},$$
$$-\rho\overline{v_j c_p T'} = \lambda_t\frac{\partial T}{\partial x_j}, \ -\rho\overline{v_j c_\alpha'} = \rho D_t\frac{\partial c_\alpha}{\partial x_j},$$
$$\lambda_t = \mu_t c_p/\mathrm{Pr}_t, \rho D_t = \mu_t/Sc_t, \mu_t = c_\mu\rho K^2/\varepsilon,$$

where μ_t, λ_t, D_t are the coefficients of turbulent viscosity, thermal conductivity, and diffusion, respectively; Pr_t, Sc_t 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 length of the mixing path is determined using the formula $l = x_3 k_t/(1 + 2.5x_3\sqrt{c_d s/h})$ taking into account the fact that the coefficient of resistance c_d in the space between the ground cover and the forest canopy base is equal to zero, while the constants k_t = 0.4 and $h=h_2-h_1$ (h_2, h_1 – height of the tree crowns and the height of the crown base). 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 [9]) type of forest.

2. Numerical Solution and Results

The boundary-value problem (1)–(14) is solved numerically. A discrete analog was obtained by means of the control volume method using the SIMPLE like algorithm (Patankar [11]). Difference equations that arise in the course of sampling were resolved by the method of SIP [11]. In order to efficiently solve this problem in a reactive flow the method of splitting according to physical processes was used. The basic idea of this method is based on the information that the physical timescale of the processes is great than chemical. In the first stage, the hydrodynamic pattern of flow and distribution of scalar functions was calculated. Then the system of ordinary differential equations of chemical kinetics obtained as a result of splitting was then integrated. The time step for integrating each function has to be smaller than the characteristic time of physical process to ensure the convergence of the numerical method. The time step was selected automatically. The accuracy of the program was checked by the method of inserted analytical solutions. Analytical expressions for the unknown functions were substituted in (1)–(14) 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. Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically. The first stage is related to increasing maximum temperature in the place of ignition with the result that a crown 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 and dispersed pyrolysis products are generated. Ignition of gaseous pyrolysis products of the crown occurs at the next stage, and that of gaseous pyrolysis products in the forest canopy occurs at the last stage. At the moment of ignition, the gas combustible products of pyrolysis burn away, and the concentration of oxygen is rapidly reduced. The isotherms of gas phase components moved in the forest canopy by the action of wind. It is concluded that the forest fire begins to spread. The results of the calculation give an opportunity to consider forest fire spread for different wind velocity, canopy bulk densities and moisture forest fuel. It is considered the effect of forest fire front on the building which is situated near from the forest. The influences of wind velocity and distance between forest and building on ignition of building are studied numerically. The results of calculations can be used to evaluate the thermal effects on the building, located near from the forest fires. The temperature fields of crown forest fire at definite moment will be interacted with the obstacle - building (Figure 2 a) and b)) and ignited it. Fig.2. shows temperature fields at the different instants moments of forest fire spread for a wind speed of 15 m/s. During this process, the surface of the wall of the building heats as a result of convection and radiation heat transfer. The wood building will be ignited at definite temperature. It depends on wind velocities, distances from the forest fire to building, the height of building and others parameters. The Figures 3-5 represent the predicted distributions of temperature on the surfaces of the wall of the building as a function of vertical coordinate for the three selected wind speed values and different distances between forest and building. In paper [12] it is showed that the wood will be ignited when its temperature exceeds 300C. The results of calculations presented on Figures 3-5 show that the surface temperature reach these values at wind velocities more than 6 m/s. The height of building in these calculations was *H*=3 m.

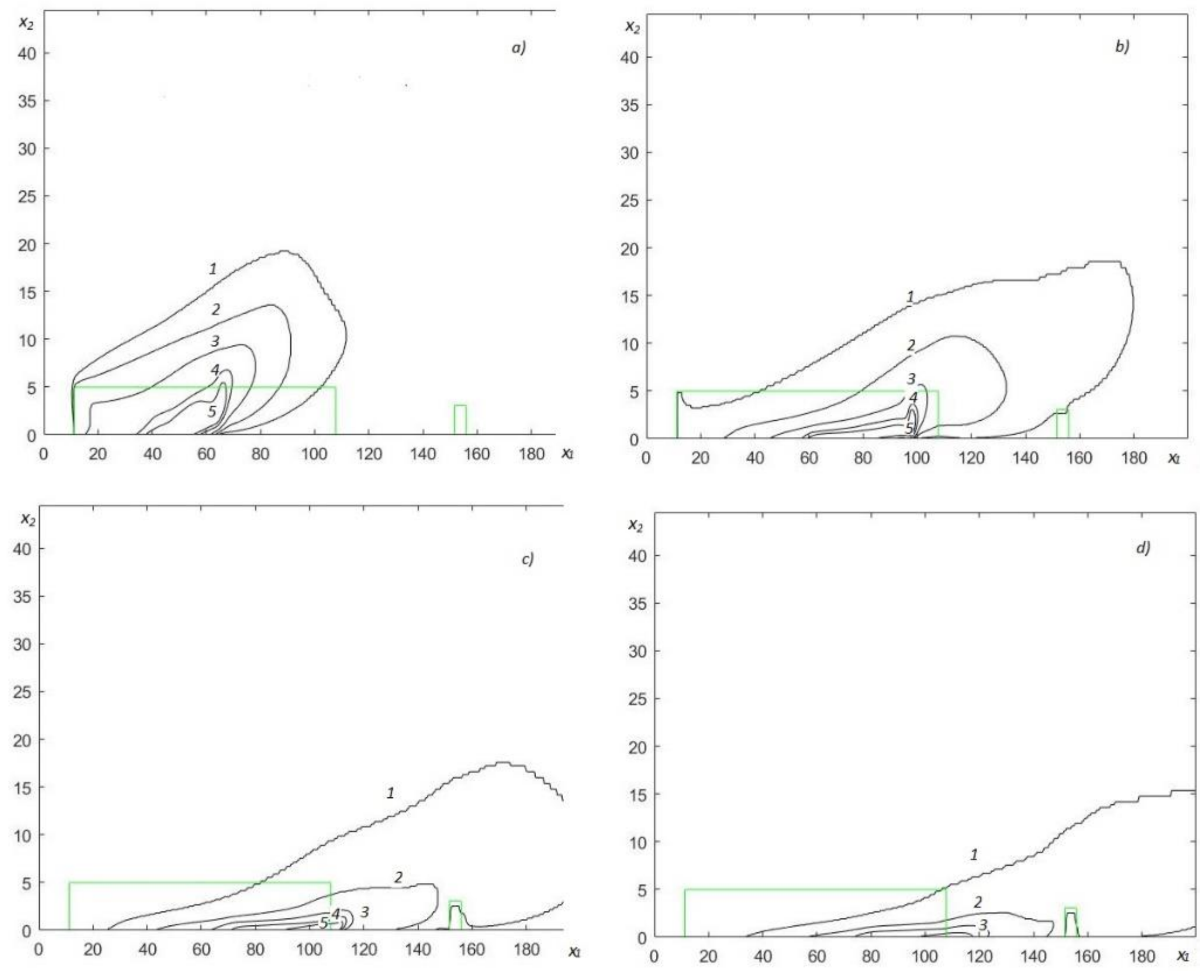

Figure 2. Gas temperature field at *a) t=15* s, *b) t=20 s, c) t=23 s, d) t=25 s* for a wind speed of 15 m/s; 1 – 1.2, 2 - 1.5, 3 – 2., 4 – 3., 5 – 4; $\bar{T}$ =T/T_e T_e=300K.

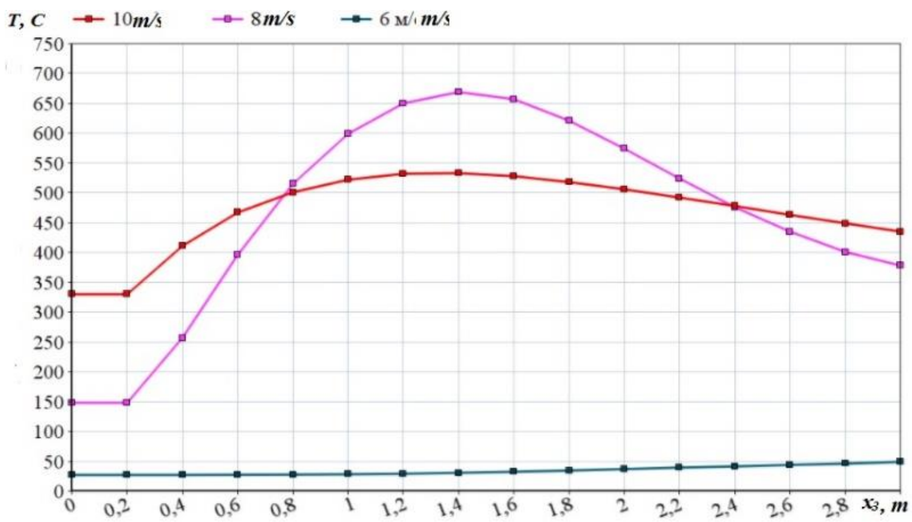

Figure 3. The distribution of temperature on the wall of the building for three wind speed values. The distance between forest and building is 21 m.

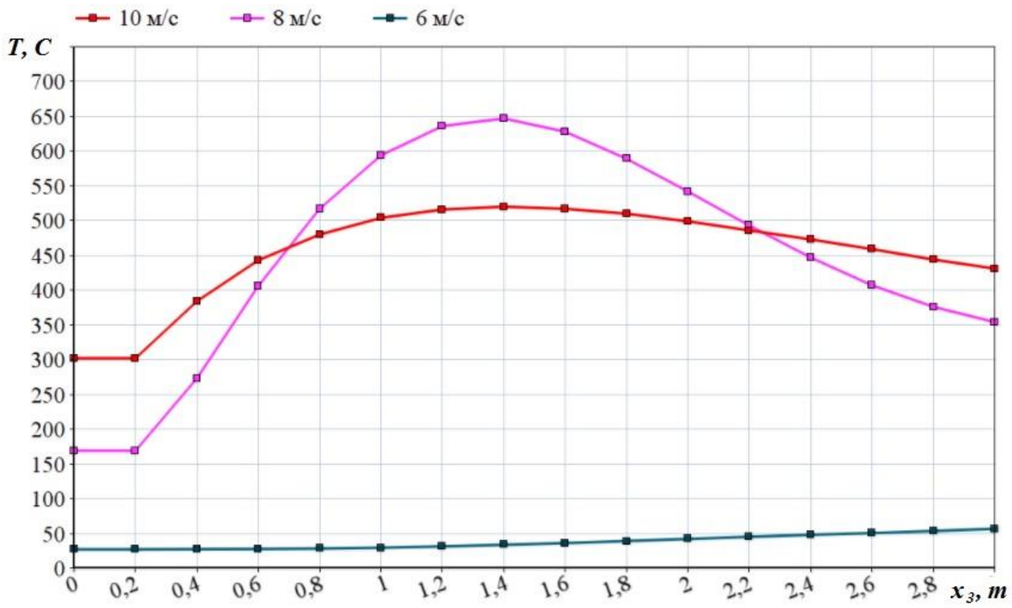

Figure 4. The distribution of temperature on the wall of the building for three wind speed values. The distance between forest and building is 26 m.

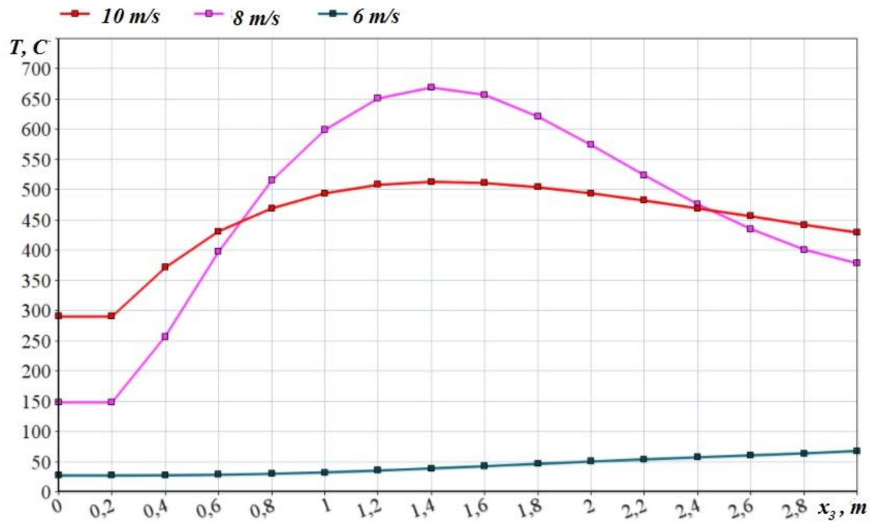

Figure 5. The distribution of temperature on the wall of the building for three wind speed values. The distance between forest and building is 31 m.

As a result of these calculations it was defined maximum safety distances between forest and building when the building would not have been ignited by forest fire (Fig. 6). The wind speed values increase from 6 to 14 m/s. Also, it was studied the influence of the height of building on the value of safety distances. When the height of building changes from 3 to 6 m, the safety distances *l* also increases (Figure 7) for different values of wind speed.

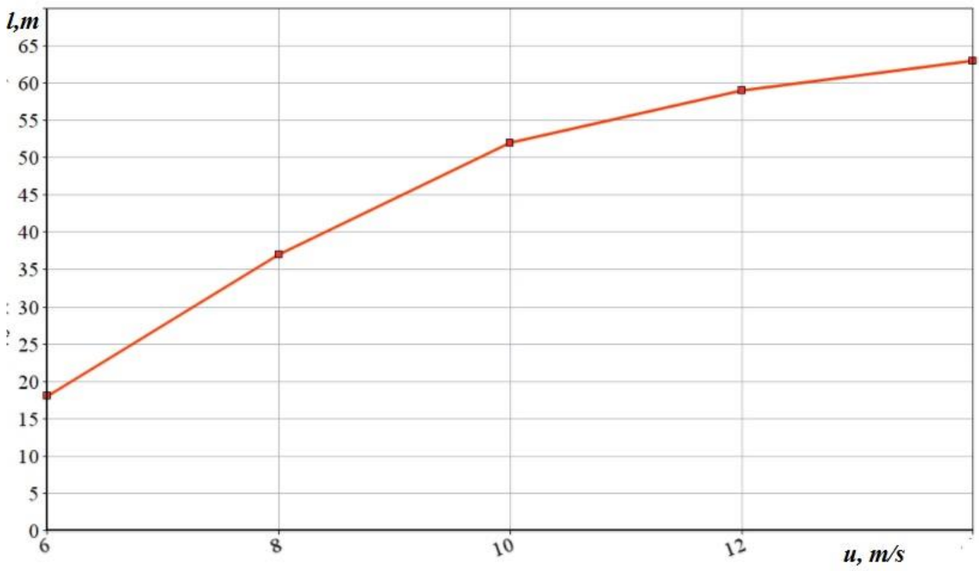

Figure 6. The dependence of safety distances between forest and building as a function of wind speed values; H=3 m.

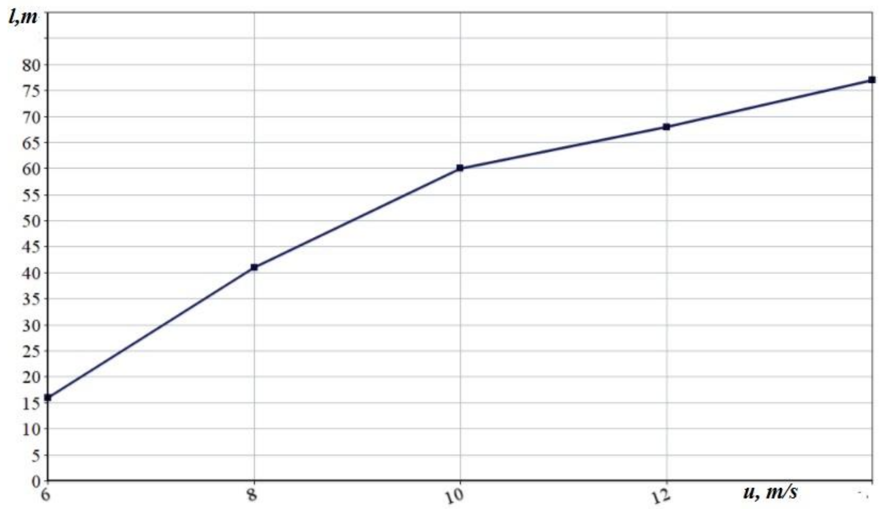

Figure 7. The dependence of safety distances between forest and building as a function of wind speed values. H=6 m.

3 Conclusions

A multiphase mathematical model of wind-aided crown forest fires propagating through heterogeneous fuel beds has been performed. It takes into account the hydrodynamic aspects of the flow and uses Arrhenius kinetics to describe the basic physics and chemical processes of thermal decomposition heating, drying, pyrolysis, and combustion. Turbulence and radiation are considered in order to improve the physical insight. It allows to investigate the dynamics of the impact of forest fires on buildings under the influence of various external conditions: a) meteorology conditions (air temperature, wind velocity etc.), b) type (various kinds of forest combustible materials) and their state (load, moisture etc.). The calculations let to get the maximum distance from the fire to the building in which the object possible ignition. It has been found that the effect of increasing the wind speed is to increase the safety distances between forest and building. The increasing of building height is observed also led to increase the safety distances between forest and building. Specific experiments are also needed to obtain more reliable information on validation of further solution of this problem.

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