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# Impact of forest fires on buildings and structures

# Воздействие лесных пожаров на здания и сооружения

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**Key words:** mathematical model; buildings; constructions; forest fire; equation; finite volume; numerical method

**Ключевые слова:** математическая модель; здания, сооружения; лесной пожар; уравнение; конечный объем; численный метод

**Abstract.** The mathematical modeling of forest fires actions on buildings and structures has 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 modeling approach is based on the use of standard non-stationary three-dimensional conservation equations that are solved numerically under the input conditions specific for large crown forest fires.

**Аннотация.** Проведено математическое моделирование действий лесных пожаров на зданиях и сооружениях с целью изучения влияния интенсивности огня и скорости ветра на возможность возгорания зданий. Верховой лесной пожар вводится как источник тепла и массы, определяемый эмпирическими значениями средней температуры верхового пожара и вертикальной скорости газа на верхней поверхности кроны в зависимости от интенсивности огня. Анализируются гидродинамическое и тепловое взаимодействия между шлейфом, потоком ветра и зданием. Модельный подход основан на использовании стандартных нестационарных трехмерных уравнений сохранения, которые решаются численно при входных условиях, характерных для крупных верховых лесных пожаров.

## *Introduction*

This paper addresses the development of a mathematical model for fires in the wildland-urban intermix**.** 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, behaviour 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. Crown fires are initiated by convective and radiative heat transfer from surface fires. However, convection is the main heat transfer mechanism. Crown fires a more difficult to control than surface. The first accepted method for prediction of crown fires was given by Rothermal [1] and Van Wagner [3]. 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], Van Wagner [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 a group of co-workers at Tomsk University (Grishin [9], Grishin et al [10]). A mathematical model of forest fires was obtained by Grishin [9] based on an analysis of known and original experimental data [9, 11], and using concepts and methods from reactive media mechanics. The physical two-phase models used in [12] may be considered as a development and extension of the formulation proposed by Grishin [9]. However, the investigation of crown fires thermal impacts on buildings and constructions has been limited mainly to cases of using simple models [13–16]. But in Russia and other countries these kinds of WUI (wildfire urban interface) models are developed very intensive [17-29]. The purpose of this paper is to study the thermal impact of forest fires on buildings and constructions. For the solution of this problem,

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it is necessary to solve the following problems: to develop a mathematical model for the spread of forest fire, to obtain a numerical solution, and to investigate the thermal effect of forest fires on buildings in order to determine the safe distances from combustion sites to buildings and structures. The present mathematical model and results of calculation are used to study the forest fire fronts interaction with buildings of different sizes.

## *Physical and mathematical model*

It is assumed that the forest during a forest 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 centre 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.

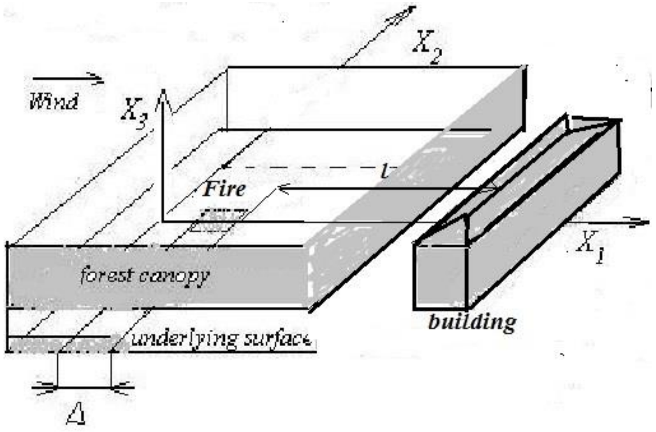

**Figure 1. The scheme of computational domain**

Problem formulated above reduces to the solution of systems of equations (1)–(7):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho v_j) = Q, \quad j = 1,2,3; \tag{1}$$

$$\rho \frac{dv_i}{dt} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}(-\rho \overline{v_i' v_j'}) - \rho s c_d v_i |\vec{v}| - \rho g_i - Q v_i, \; i = 1,2,3; \tag{2}$$

$$\rho c_p \frac{dT}{dt} = \frac{\partial}{\partial x_j}(-\rho c_p \overline{v_j' T'}) + q_5 R_5 - \alpha_v (T - T_s); \tag{3}$$

$$\rho \frac{dc_\alpha}{dt} = \frac{\partial}{\partial x_j}(-\rho \overline{v_j' c_\alpha'}) + R_{5\alpha} - Q c_\alpha, \quad \alpha = 1,3; \tag{4}$$

$$\frac{\partial}{\partial x_j}\left(\frac{c}{3k}\frac{\partial U_R}{\partial x_j}\right) - k(cU_R - 4\sigma T_S^4) = 0; \tag{5}$$

$$\sum_{i=1}^{4} \rho_i c_{pi} \varphi_i \frac{\partial T_S}{\partial t} = q_3 R_3 - q_2 R_2 + k(cU_R - 4\sigma T_S^4) + \alpha_V (T - T_S); \tag{6}$$

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

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

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

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

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

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

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

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

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

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

Here and above $\frac{\mathrm{d}}{\mathrm{d}t}$ is the symbol of the total (substantial) derivative; $\alpha_V$ is the coefficient of phase exchange; $\rho$ - 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, $c_{pi}$, $\rho_i$, $\varphi_i$ – 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; $c_\alpha$ – 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; $M_\alpha$, $M_C$, 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 $R_{52}$

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

Here $\nu_g$ – mass fraction of gas combustible products of pyrolysis, $\alpha_4$ and $\alpha_5$ – 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 $E_i$) are evaluated using data for mathematical models [9, 10].

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

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

$$\varphi_{1e} = \frac{d(1-\nu_z)}{\rho_1}, \varphi_{2e} = \frac{dW}{\rho_2}, \varphi_{3e} = 0,$$

where *d* – bulk density for surface layer, $\nu_z$ – 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)–(9) 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:

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

$$-\rho\overline{v_j c_p T'} = \lambda_t \frac{\partial T}{\partial x_j}, \; -\rho\overline{v_j c_\alpha'} = \rho D_t \frac{\partial c_\alpha}{\partial x_j},$$

$$\lambda_t = \mu_t c_p / \mathrm{Pr}_t, \rho D_t = \mu_t / Sc_t, \mu_t = c_\mu \rho K^2 / \varepsilon,$$

where $\mu_t$, $\lambda_t$, $D_t$ 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. The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different (for example pine [1, 9, 10]) type of forest.

## *Result and Discussion*

The boundary-value problem (1)–(14) is solved numerically. Buildings were set using a method of fictitious areas [19].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. A discrete analog was obtained by means of the control volume method using the SIMPLE like algorithm (Patankar [30]). Difference equations that arise in the course of sampling were resolved by the method of SIP [31]. 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 prolysis 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. 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. At $V_e \neq 0$, the wind field in the forest canopy interacts with the gas-jet obstacle that forms from the forest fire source and from the ignited forest canopy and burn away in the forest canopy. 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 wind and temperature fields interact with the obstacle – building (Figure 2 a) and b)).

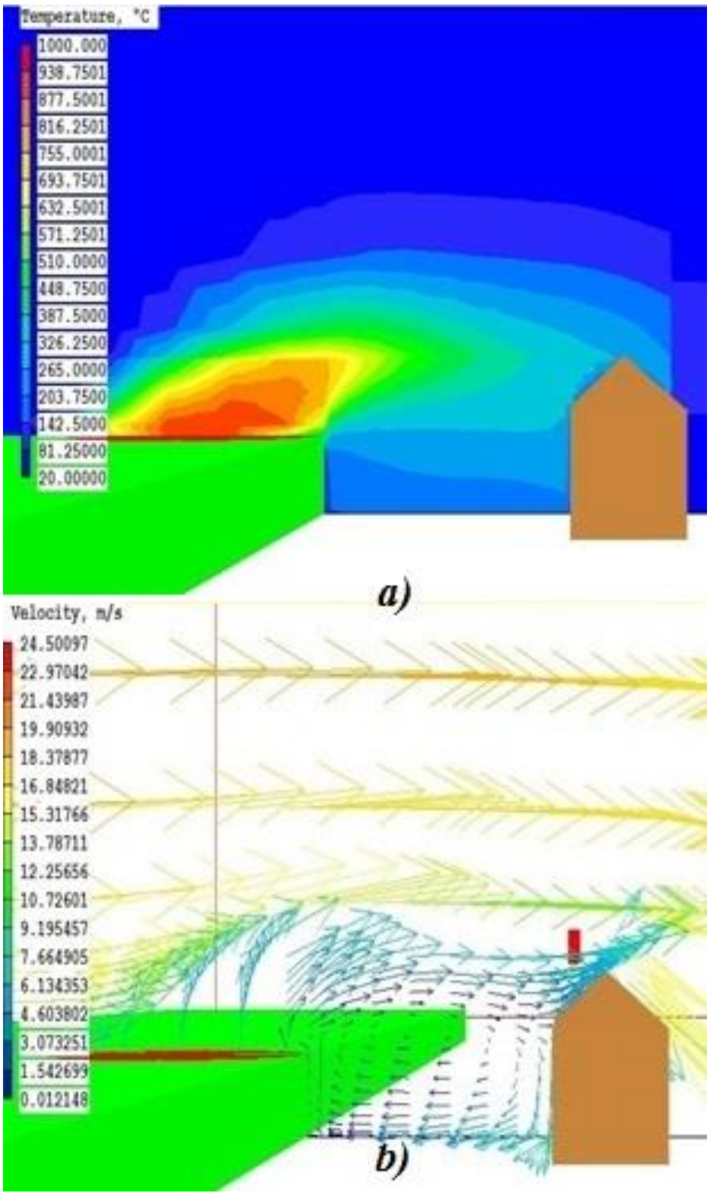

**Figure 2. The distributions of temperature a) and velocity b) near from the building**

Figure 2 shows the simulation results of the wall temperatures at different distances between crown forest fire and wooden building (20×50×20 meters) for different values of wind speeds from 3 to 15 m/s. An analysis of this dependence (Figure 3) shows the following:

Fire wood construction with a wind speed of 3 m/s will start at a distance of 15-16 meters from the forest fires;

Fire wood construction with a wind speed of 5 m/s will start at a distance of 26-27 meters from the forest fires ;

Fire wood construction with a wind speed of 10 m/s will start at a distance of 39-40 meters from the forest fires;

Fire wood construction with a wind speed of 15 m/s will start at a distance of 46-47 meters from the forest fires.

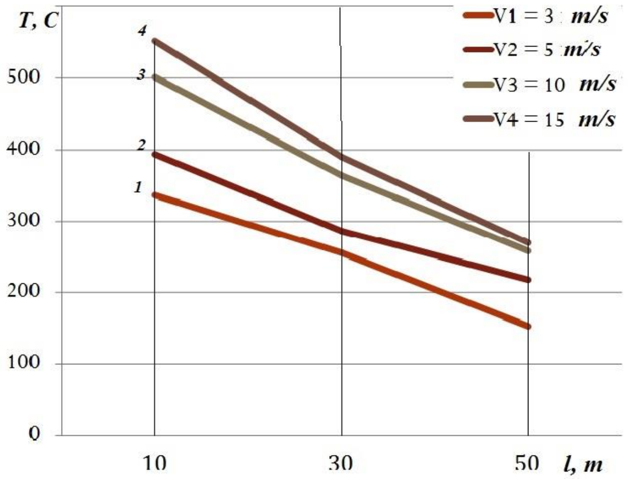

**Figure 3. The dependence of the temperature on the walls of a wooden house for different wind speeds (3-15m/s) for the different distances *l* (10-50 m)**

Then using the results of calculation it is plotted the temperature on the walls of a wooden building (12×15×12 meters) for wind speeds from 3 to 15 m/s. The results are shown in Figure 4.

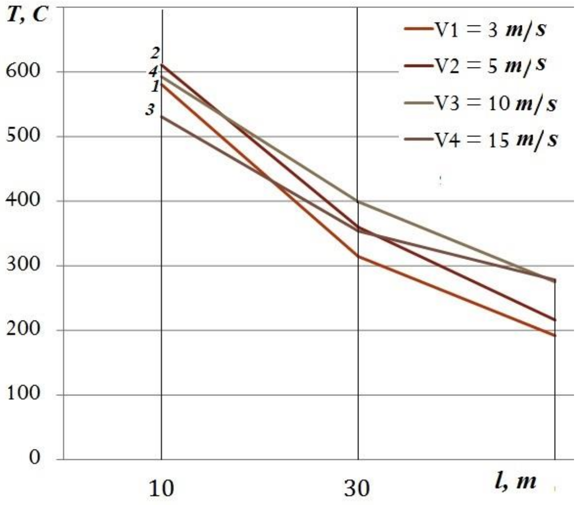

**Figure 4. The dependence of the temperature on the walls of a wooden house for different wind speeds (3-15m/s) for the distances *l* (10-50 m)**

An analysis of this dependence (Figure 4) shows the following:

1. Fire wood construction with a wind speed of 3 m/s will start at a distance of 32–33 meters from the forest fires;

Fire wood construction with a wind speed of 5 m/s will start at a distance of 38–39 meters from the forest fires;

Fire wood construction with a wind speed of 10 m / s will start at a distance of 43–44 meters from the forest fires;

Combustion of wooden buildings at a wind speed of 15 m/s will start at a distance of 42–43 meters from the forest fires.

## Conclusion

The model proposed there gives a detailed picture of the change in the velocity, temperature and component concentration fields with time. 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.

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