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SCENARIO MODELING OF THERMAL INFLUENCE FROM FOREST FIRE FRONT ON A CONIFEROUS TREE TRUNK

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Abstract. Scenario research results of heat transfer and tissue damage in three-layered tree trunk influenced by heat flux from forest fire are presented. The problem is solved in two-dimensional statement in polar coordinates. The typical range of influence parameters (heat flux from forest fire front, trunk radius, coniferous species, air temperature, duration of exposure and distance from fire line) is considered. Temperature distributions in different moments of time are obtained. Condition of tree damage by forest fire influence is under consideration in this research. Information summarized using tables with scenario and fire consequences results.

1 Introduction

Fire damages (thermal traumas) of trees in forest stand occur as a result of direct influence of forest fire more often. Fire damages involve either death of trees or their weakness. It leads to trees fall or their infection by harmful insects and mushrooms. In addition, thermal traumas cause anatomic changes in trees and not only weakness, but also strengthening of their growth and bearing [1-3].

As a result of fire influence trees get various damages which are shown in the form of [1-3]:
-trunk burns;
-burns of roots;
-crown burns.

Influence of surface forest fire on trees is often limited to an easy superficial burn or bark burn that can be painless for a tree if fire is not influence on cambium. Cambium is sensitive even to small rise of temperature. An external sign of cambium death is its russeting. According to literary data cambium is dead at heating to 57 °C. Dying off of the big sites of cambium in trunk or root circle can lead to drying of tree [1-3].

Phloem defeat at a root neck, around of a tree trunk and partially on a trunk circle is observed on forested territory where has passed surface fire of low intensity. Therefore the part of trees within next year will have a dying off of roots that will lead to mortality of

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trees. It is established by results of the conducted researches, that there is phloem dying off at all types of forest fire. Consequently, possible restoration of forest stands on these sites is difficult to expect. Besides, mycelium presence on the considerable area of wood laying on a root and radical part of trunk of a pine (oak and birch) on all height of trunk will sharply reduce quality of wood. It leads to favorable conditions for intensive growth of various mushrooms and defeat of wood by insects [4].

Now the majority of papers is devoted to the analysis of an actual statistical material on forest fire incidents and their ecological consequences [5,6]. However, development of information-computation systems for geoecological monitoring of large forests at active forest fires on the basis of physically proved mathematical models of heat transfer in structure of the trees forming a forest stand may become one of perspective directions [7,8].

The purpose of the present work is scenario modeling of heat transfer in tree trunk structure of conifers at influence of radiation from forest fire front in flat statement and determination of conditions for thermal defeats formation.

2 Physical and Mathematical Statements

The mathematical model is developed taking into account following assumptions. Separately standing tree of coniferous breed is considered. For definiteness calculations is conducted for pine, fir and silver fir. The tree trunk is considered without presence of branches within this mathematical model. The trunk is considered as a three-layer structure (bark, inner bark and a core). Thermophysical properties of each layer material do not depend on temperature. Influence of moisture evaporation from external and trunk inside layers is neglected. Process of thermal decomposition of trunk wood on the basis of the kinetic scheme [9] is considered. Geometry of decision area is shown on fig. 1.

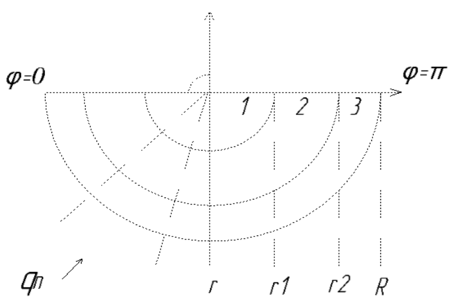

Fig. 1. Geometry of decision area: 1 – core; 2 – inner bark; 3 – bark.

Heat transfer processes in layered structure of tree trunk is described by the nonlinear non-stationary differential equations of heat conductivity with corresponding initial and boundary conditions:

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = \frac{\lambda_1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right) + \frac{\lambda_1}{r^2}\frac{\partial^2 T_1}{\partial \varphi^2} - q_p k_1 \rho_1 \varphi_1 \exp\left(-\frac{E_1}{RT_1}\right),$$

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = \frac{\lambda_2}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right) + \frac{\lambda_2}{r^2}\frac{\partial^2 T_2}{\partial \varphi^2} - q_p k_1 \rho_2 \varphi_1 \exp\left(-\frac{E_1}{RT_2}\right),$$

$$\rho_3 c_3 \frac{\partial T_3}{\partial t} = \frac{\lambda_3}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_3}{\partial r}\right) + \frac{\lambda_3}{r^2}\frac{\partial^2 T_3}{\partial \varphi^2} - q_p k_1 \rho_3 \varphi_1 \exp\left(-\frac{E_1}{RT_3}\right),$$

$$T_i\big|_{t=0} = T_{i0},$$

$r=R,\ \varphi \in (\varphi_1, \varphi_2),\ -\lambda_1 \frac{\partial T_1}{\partial r} = q_{ff}$,

$r=0,\ -\lambda_1 \frac{\partial T_1}{\partial r} = 0$,

$\varphi=0,\ -\lambda_i \frac{\partial T_i}{\partial \varphi} = 0$,

$\varphi=\pi,\ -\lambda_i \frac{\partial T_i}{\partial \varphi} = 0$,

$r=R1,\ -\lambda_1 \frac{\partial T_1}{\partial r} = -\lambda_2 \frac{\partial T_2}{\partial r},\ T_1 = T_2$,

$r=R2,\ -\lambda_2 \frac{\partial T_2}{\partial r} = -\lambda_3 \frac{\partial T_3}{\partial r},\ T_2 = T_3$,

The kinetic scheme of pyrolysis:

$$\rho_1 \frac{\partial \varphi_1}{\partial t} = -k_1 \rho_1 \varphi_1 \exp\left(-\frac{E_1}{RT_1}\right), \qquad \varphi_i\big|_{t=0} = \varphi_{i0} ,$$

$$\rho_2 \frac{\partial \varphi_1}{\partial t} = -k_1 \rho_2 \varphi_1 \exp\left(-\frac{E_1}{RT_2}\right), \qquad \varphi_i\big|_{t=0} = \varphi_{i0} ,$$

$$\rho_3 \frac{\partial \varphi_1}{\partial t} = -k_1 \rho_3 \varphi_1 \exp\left(-\frac{E_1}{RT_3}\right), \qquad \varphi_i\big|_{t=0} = \varphi_{i0} ,$$

$$\sum_{i=1}^{2} \varphi_i = 1 ,$$

$$\rho_1 \frac{\partial \varphi_1}{\partial t} = -k_1 \rho_1 \varphi_1 \exp\left(-\frac{E_1}{RT_1}\right),\ \varphi_i\big|_{t=0} = \varphi_{i0} ,$$

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$$\rho_3 \frac{\partial \varphi_1}{\partial t} = -k_1 \rho_3 \varphi_1 \exp\left(-\frac{E_1}{RT_3}\right),\ \varphi_i\big|_{t=0} = \varphi_{i0} ,$$

$$\sum_{i=1}^{2} \varphi_i = 1 ,$$

Where T_i, ρ_i, c_i, λ_i - temperature, density, thermal capacity and heat conductivity of tree trunk layers (1 - core, 2 – inner bark, 3 - bark). φ_i - volume fraction (1 - dry organic substance, 2 - gas). k_1, E_1 - thermokinetic constants of wood pyrolysis. q_p - thermal effect of pyrolysis. R - universal gas constant. r, φ - spatial coordinates. t - time coordinate. q_{ff} - radiant thermal flux from forest fire front.

The problem is solved by a method of finite differences. The multidimensional differential equations are solved by a locally-one-dimensional method. Marching method [10] is used for the decision of finite-difference analogues. Data of experimental burns, conducted by employees of the Institute of forest of the Siberian Branch of the Russian Academy of Science in vicinities of Krasnoyarsk are used for development of the basic

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scenarios of influence of radiant thermal flux from forest fire front. Dependence [11] is used for an estimation of thermal flux value from forest fire front:

$y = 326.37e^{-0.2791x}$.

Where x - distance to a fire front, m. y – thermal flux density, kW/m^2.

3 Results and Discussion

Numerical realization for mathematical model of heat transfer in layered structure of coniferous tree trunk is carried out using programming language of high level Object Pascal. IBM PC-compatible computer with Intel Core 4 Quad 3 GHz processor unit and 8 GB RAM was used for computing experiments. Using computation system based on multi-core processor with Hyper Threading technology for numerical realization of two-dimensional mathematical model allows to use physically proved resource effective algorithm for program realization. Various scenarios have been developed for an estimation of thermal influence on a tree trunk of coniferous breed. Typical distributions of temperature in layered structure of a tree trunk are presented to the certain moment of time on Fig. 2. Description of scenarios of fire influence is presented in table 1.

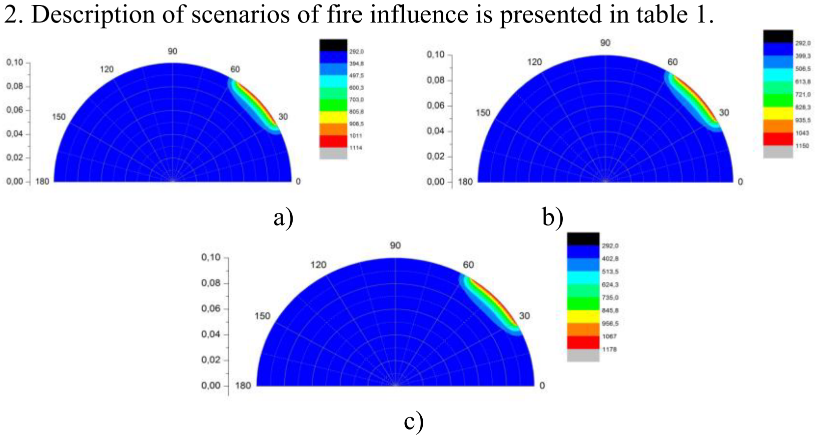

Fig. 2. Fields of temperature in layered structure of coniferous tree at the moment of time t=350 s: a - pine, b – silver fir, c – fir.

Table 1. The description of typical scenarios of influence of a radiant thermal stream from forest fire front on a coniferous tree trunk.

Season	Conifers	Distance to fire front, m	Core radius, m	Inner bark radius, m	Exposure time, s
Summer	Silver Fir	4	0.08	0.09	500
Summer	Pine	4	0.08	0.09	500
Summer	Fir	4	0.08	0.09	500

Short-term influence of radiation from forest fire front (few minutes) on coniferous tree trunk was accepted within the present scenario modeling. This assumption corresponds to the real scenario of forest fire behavior and characteristic velocity of forward forest fire front distribution in forest with coniferous trees.

The analysis of the obtained distributions of temperature shows, that eventually there is an intensive warming up, as bark layer and inner bark layer of coniferous tree trunk at influence of radiation from forest fire front. There is a thermal decomposition of wood and formation of thermal trauma site at reaching of critical temperatures in a tree trunk.

Typical data on conditions of thermal defeat of coniferous tree trunk in inner bark are cited in tables 1, 2. The analysis of tables allows to draw a conclusion, that longer influence of radiation from forest fire leads to thermal defeat of inner bark at smaller distances from a fire and density of thermal radiation. However, using thermophysical model is impossible to establish the fact of the subsequent tree mortality in forest stand. Temperature distributions presented on fig. 2 show, that the field of temperatures in tree trunk for various coniferous breeds has qualitative similarity. Appreciable distinctions of maximum temperatures are observed in bark layer. These distinctions decrease with spreading heat wave deep into a tree trunk. According to [12], there are distinctions in long-term prospect of dying off of trees of various breeds at rather identical influence of the raised temperatures. Besides, the range of influence time of the raised temperature in definite point of tree trunk and not only reaching of critical temperature are meant [13]. The given work has the big prospects of integration of results of numerical modeling (temperature fields in a tree trunk) with natural observations data for forest stands mortality in after fire period.

Table 2. Conditions of thermal defeat in tree trunk at influence time t=500 s. Surface forest fire of high intensity [11].

Conifers	Distan-ce, m	Heat flux, kW/m^2	Air tempera-ture, K	Trunk radius, m	Exposure time, s	Pyro-lysis	Thermal trauma
Pine	4	106.87	300	0.1	500	Yes	Yes
Silver fir	4	106.87	300	0.1	500	Yes	Yes
Fir	4	106.87	300	0.1	500	Yes	Yes

4 Conclusion

Scenario modeling results of heat transfer in coniferous tree trunk are resulted at influence of a radiant thermal flux from forest fire front in present paper. Conditions of thermal defeats occurrence in coniferous tree trunk are determined. Typical scenarios of forest fire danger (characteristic for summertime) were considered. Numerical modeling results for typical coniferous trees (fir, silver fir and pine) are obtained. Research of the heat transfer basic laws is carried out in layered structure of tree trunk at influence of surface forest fire of high intensity. Development of similar models opens prospects to creation of new generation information systems on the basis of the deterministic mathematical models of heat transfer in tree trunk. Working out of the complex deterministic-probabilistic approach for an estimation of forest fire ecological consequences with attraction of forest fire danger prognostic modeling results [14,15], mathematical models of forest fire influence on humans [16] and modern information technologies is possible [17,18].

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