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Mathematical Simulation of Heat Transfer in Heterogenous Forest Fuel Layer Influenced by Heated Up to High Temperatures Steel Particle

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Abstract. Heterogeneity of forest fuel layer renders the important influence on forest fire occurrence processes. One of sources of the raised temperature on forested territories is metal particles heated up to high temperatures. Such particles can be formed as a result of welding of metals on forested territories. The present paper represents the heat transfer research in forest fuel at the influence of metal particle heated up to high temperatures. The heterogonous forest fuel layer with inclusions of small wooden branches and chips is considered. Such object research is urgent especially at fire forecasting on forest cutting. The technology of mathematical simulation is used. The two-dimensional problem of heat transfer in forest fuel layer structure with wood inclusions is solved.

1. Introduction

Forest fires occurrence is an actual problem for many countries with forested territories (Russia, USA, Canada, Southern Europe and others) [1]. Liquidation of forest fire consequences demands considerable expenses of human, technical and financial resources [2]. Therefore now it is urgent to solve this problem even before its occurrence by means of ignition forecasting in forests [3]. Forest fuel layer ignition by various sources of local heating, such as particles heated up to high temperatures, is a major stage of forest fire occurrence [4,5]. In turn, heat transfer processes in the forest fuel layer determine many laws of its ignition at the influence of local heating source [3]. It is necessary to notice that forest fuel layer in real large forest is not structurally homogeneous and contains wood inclusions, for example, thin branches of trees [6]. Therefore it is currently important to investigate the heat transfer in forest fuel layer taking into account its structural heterogeneity. The perspective tool of research is the approach of mathematical simulation of heat transfer processes in forest fuel layer using computer facilities [7].

The purpose of our work is to develop and research the heat transfer mathematical model in forest fuel layer taking into account the non-uniform wood inclusions under the influence of a particle heated up to high temperature.

It is necessary to notice that such a factor of forest fire occurrence as particles, heated up to high temperatures, is insufficiently studied. Basically the research was carried put under the experimental analysis of forest fuel ignition by particles heated up to high temperatures [8, 9]. The basic influence is given to particles of sufficiently large size. Ignition delay times of forest fuel at the influence of

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steel and carbonaceous particles of small size are established only in works [10, 11]. Authors [10, 11] used a specially developed experimental stand on physical modelling of forest fuel ignition processes. Physical mechanism of forest fuel ignition at their local heating has been identified as result of such experiments. The research has been conducted for homogeneous packing of forest fuel layer. At the same time it is necessary to investigate ignition processes of structurally non-uniform layers with wood inclusions of small sizes (for example, thin branches of trees). Forest fuel layer inert warming stage, which also defines the subsequent forest fuel thermal decomposition and ignition processes, precedes the ignition process [12]. Therefore it is necessary to analyze the heat transfer processes in a structurally non-uniform layer of forest fuel at the influence of a particle heated up to high temperatures.

2. Physical and Mathematical Statement

The present paper considers the catastrophic scenario of forest fires occurrence [13] when the moisture is absent in forest fuel layer. The events of last years in Russia, USA and Australia prove an urgency of this development of fire-dangerous scenario. The following physical model of investigated process is considered. Forest fuel layer with non-uniform inclusions of wood (thin branches of trees) is located on the spreading surface. The material of inclusions differs from the forest fuel by thermophysical characteristics. The metal particle heated up to high temperatures drops out on the forest fuel layer. This variant of dropping the metal particles corresponds to the scenario of anthropogenous loading on the forested territory. The forest fuel layer and inclusions are inertly heated up. It is considered that conduction is the main heat transfer mechanism in this system. It is accepted that contact of particle and forest fuel layer is ideal. The geometry of decision area is given on figure 1.

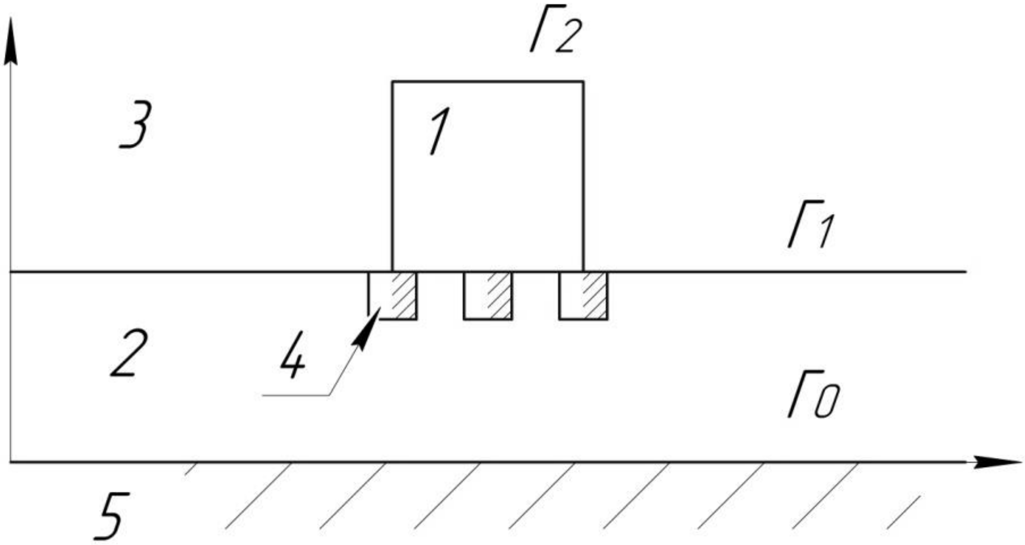

Figure 1. The scheme of decision area: 1 – heated up to high temperatures particle; 2 – forest fuel layer; 3 - air; 4 - inclusion in the form of wood; 5 - top soil layer.

Heat transfer processes in the system "particle-forest fuel layer-inclusions" are described mathematically by the non-stationary non-linear differential equations of heat conductivity with the corresponding initial and boundary conditions. The energy equations are given below:

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = \lambda_1 \frac{\partial^2 T_1}{\partial x^2} + \lambda_1 \frac{\partial^2 T_1}{\partial z^2}, \quad (1)$$

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = \lambda_2 \frac{\partial^2 T_2}{\partial x^2} + \lambda_2 \frac{\partial^2 T_2}{\partial z^2} - q_p k_0 \varphi \rho_2 \exp\left(-\frac{E}{RT_2}\right), \quad (2)$$

$$\rho_3 c_3 \frac{\partial T_3}{\partial t} = \lambda_3 \frac{\partial^2 T_3}{\partial x^2} + \lambda_3 \frac{\partial^2 T_3}{\partial z^2} - q_p k_0 \varphi \rho_3 \exp\left(-\frac{E}{RT_3}\right), \quad (3)$$

Boundary conditions on the border with the air environment:

$$\lambda_1 \frac{\partial T_1}{\partial z} = \alpha (T_1 - T_e), \quad (4)$$

Boundary conditions on the border "particle-forest fuel":

$$\lambda_1 \frac{\partial T_1}{\partial z} = \lambda_2 \frac{\partial T_2}{\partial z}, \ T_1 = T_2, \quad (5)$$

Boundary conditions on the border "particle-inclusion":

$$\lambda_1 \frac{\partial T_1}{\partial z} = \lambda_3 \frac{\partial T_3}{\partial z}, \ T_1 = T_3, \quad (6)$$

Boundary conditions on the border "forest fuel-inclusion":

$$\lambda_2 \frac{\partial T_2}{\partial z} = \lambda_3 \frac{\partial T_3}{\partial z}, \ T_2 = T_3, \quad (7)$$

$$\lambda_2 \frac{\partial T_2}{\partial x} = \lambda_3 \frac{\partial T_3}{\partial x}, \ T_2 = T_3, \quad (8)$$

Boundary conditions on the border "forest fuel-soil":

$$T_2 = T_s, \quad (9)$$

Boundary conditions on the border of decision area:

$$\lambda_1 \frac{\partial T_1}{\partial x} = 0, \quad (10)$$

$$\lambda_2 \frac{\partial T_2}{\partial x} = 0, \quad (11)$$

The kinetic equations of forest fuel and wood inclusions pyrolysis:

$$\rho_2 \frac{\partial \varphi}{\partial t} = -k_p \rho_2 \varphi \exp\left(-\frac{E}{RT_2}\right), \quad (12)$$

$$\rho_3 \frac{\partial \varphi}{\partial t} = -k_p \rho_3 \varphi \exp\left(-\frac{E}{RT_3}\right), \quad (13)$$

Initial conditions:

$$t = 0, \quad T_i = T_{i0}, \quad i = 1,2,3, \quad \varphi = \varphi_0 \quad (14)$$

Where T_i – temperature (1 – heated particle, 2 – forest fuel layer, 3 - inclusion in forest fuel layer); T_s – soil temperature; T_e – environmental temperature; ρ_i, c_i, λ_i – density, thermal capacity and heat conductivity (1 - heated particle, 2 – forest fuel layer, 3 – inclusion in forest fuel layer); t - time; x, z - spatial coordinates; q_p - thermal effect of pyrolysis; k_0 - pyrolysis pre-exponential factor; E – energy of pyrolysis activation; R - universal gas constant.

3. Results and Discussion

The finite difference method has been used for numerical implementation of the offered model. The two-dimensional equations of heat conductivity have been solved by the locally-one-dimensional method of Samarskiy A.A. Difference analogues of the one-dimensional equations have been solved by marching method in combination with a method of simple iteration. The program component has been developed for numerical modelling of heat transfer in the structurally non-uniform layer of forest fuel in high level language Object Pascal.

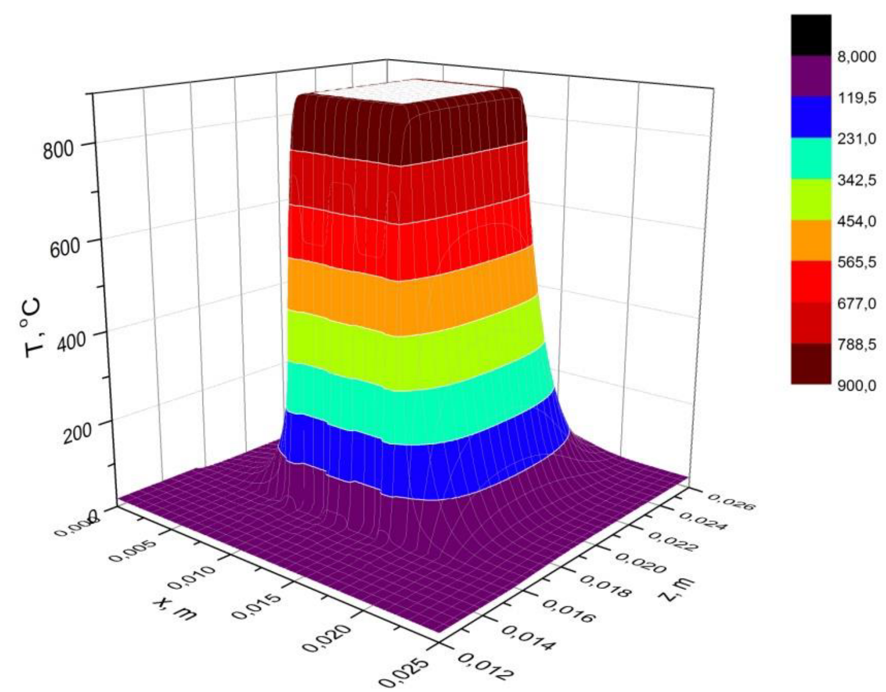

Figure 2. Typical temperature distribution in system «forest fuel-inclusion-particle» at 1 second of heated particle influence

The scenario of spring fire-dangerous season in the territory of Timiryazevskiy forestry enterprise of Tomsk region has been chosen for numerical modelling. For definiteness the environment parameters typical for May were used. The computing experiments have been made on mathematical modelling of heat transfer processes in the structurally non-uniform layer of forest fuel (pine needles) with inclusions from thin pine branches. In the considered scenario the structural heterogeneities have been located directly on the border of contact with a particle heated up to high temperatures. Monolithic structure of forest fuel layer was used at the modelling approach. Typical distribution of temperature in the system “particle-forest fuel layer-inclusion” is given on figure 2. Typical temperature dependence on time in forest fuel layer between two wooden inclusions is given on figure 3.

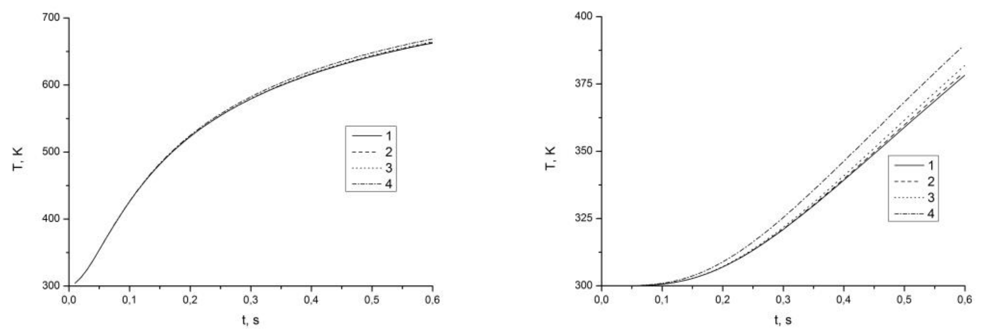

Figure 3. Temperature depend on time in forest fuel between the two two inclucions: a) in upper layer of forest fuel; b) in more deep layer of forest fuel. Distance to inclusion: 1 – 1.5 mm, 1 mm, 0.6 mm, 0.3 mm.

The analysis of the dependences presented in figure 3, shows distinctions in heat transfer in forest fuel layer at the presence of inclusions in its structure. Warming up is caused mainly by heat transfer on vertical coordinate from heated up to high temperatures particle in surface layer. Impact from more heated wooden inclusion also influences on heat transfer in an adjoining material in deeper layers of forest fuel.

4. Conclusions

The mathematical model of heat transfer in the structurally non-uniform forest fuel layer influenced by a steel particle heated to high temperatures is developed as a result of the present work. Fields of temperatures in the system “particle-forest fuel layer-inclusions” during the various moments previous to ignition of forest fuel layer are obtained. As a result of computing experiments it is established that the presence of inclusions does not significantly influence on heat transfer processes in the structurally non-uniform forest fuel layer for the model of monolithic structure of this layer. Thus, the developed mathematical technique can be applied for creating the new systems for forest fire danger forecasting [14-16] based on deterministic approach. The specified mathematical technique can be applied both for homogeneous, and for non-uniform layers of forest fuels.

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