NUMERICAL SIMULATION OF HEAT TRANSFER IN SOIL LAYER DURING FOREST FIRE IN COMPARISON WITH EXPERIMENTAL DATA

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ABSTRACT

Forest fires affect vegetation, atmosphere, living organisms and soils. The nature of these influences is different. After a fire the elemental composition changes, water erosion occurs, and the soil micro fauna dies in soil. Therefore, it is important to be able to assess and predict the effects of a forest fire on the upper soil horizon. The goal of the work is numerical simulation of heat transfer in the near-surface layer of the soil when exposed to an inert heat source, taking into account the available experimental data. An experimental equipment was developed that allowed physically simulating the process of inert heating of the near-surface soil layer. An electric heater was used. Thermocouples with a step of 1 cm along the vertical were placed in the soil layer. An electrical signal through an analog-to-digital converter is fed to a personal computer. Data is processed using the LabView program. Thus, an array of data is generated, which demonstrates the experimental dependence of temperature on time at various depths of the soil layer. Then a one-dimensional mathematical model of heat transfer in the soil layer was developed under the influence of an inert heat source. The heating rate was set on the basis of the available experimental data. Mathematically, heat transfer in the soil layer is described by non-stationary heat conduction equations with the corresponding initial and boundary conditions. Scenarios of the impact of an inert heater on the soil layer have been developed. The verification of the mathematical model was carried out using experimental data obtained at a heater temperature of 130 °C. Satisfaed agreement was obtained between experimental data and numerical results for some scenarios. Then, other scenarios of an inert heater effect were simulated using mathematical model. Conclusions on the work done are formulated.

Keywords: *soil, fire, heat transfer, simulation, experiment*

INTRODUCTION

In the last century, forest fires have become a catastrophic phenomenon [1], which manifests itself in many countries of the world. To date, the technology of prognostic modeling of forest fire danger has been successfully developed. The output of forest fire danger models can be used in systems for assessing and predicting the environmental consequences of forest fires.

Soil thermophysics is one of the most important branches of technical and agronomic physics [2], [3]. The thermal effects of forest fires on the surface layers of the soil are important [4]. After the fires in the soil, a change in the physicochemical properties, water balance and activity of microorganisms is observed [5], [6], [7], [8]. Therefore, an important problem that needs to be solved is the development of mathematical models for assessing the effect of thermal conditions of forest fires on soil.

The purpose of the study is a numerical study of the inert heat effect on the soil layer, taking into account the experimental data.

STATEMENT

The soil layer is considered as a two-layer system [9], in which zones rich in organic matter (upper layer 5 cm thick) and clay (lower layer 5 cm thick) can be marked out. Heat transfer to the subsequent layers in the work is taken into account by setting boundary conditions of the 3rd kind using the heat transfer coefficient. It is supposed that heat transfer in the "clay-layer-organic-layer-forest fuel-air" system is carried out only due to the mechanism of thermal conductivity. Model soil is considered without reference to a specific soil type [10]. The solution area is represented by four layers: clay, organic layer, forest fuel layer and air above the forest fuel layer. The boundary conditions of the 4th kind are set at the interface of the layers. Unperturbed temperature values (temperatures deep in the soil and in the air, respectively) are set at the boundary of the computational domain, taking into account heat transfer coefficients. In the forest fuel layer, an area of elevated temperature corresponding to the source of ignition is given. Gas phase processes in the air layer in this version of the mathematical model are neglected.

In accordance with physical assumptions, mathematically, the process of heat propagation in soil is described by a system of heat conduction equations with corresponding initial and boundary conditions.

The energy equation for the air layer:

$$\rho_g c_g \frac{\partial T_g}{\partial t} = \lambda_g \frac{\partial^2 T_g}{\partial z^2},$$

The energy equation for the layer of forest fuel:

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = \lambda_1 \frac{\partial^2 T_1}{\partial z^2},$$

The energy equation for topsoil:

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = \lambda_2 \frac{\partial^2 T_2}{\partial z^2},$$

The equation of energy for the lower layer of soil

$$\rho_3 c_3 \frac{\partial T_3}{\partial t} = \lambda_3 \frac{\partial^2 T_3}{\partial z^2},$$

Boundary conditions for equations:

$$\Gamma_0 \qquad \alpha_1 (T - T_{es}) = \lambda_3 \frac{\partial T_3}{\partial z},$$

$$\Gamma_1 \qquad \lambda_3 \frac{\partial T_3}{\partial z} = \lambda_2 \frac{\partial T_2}{\partial z}, \qquad T_3 = T_2,$$

$$\Gamma_2 \qquad \lambda_2 \frac{\partial T_2}{\partial z} = \lambda_1 \frac{\partial T_1}{\partial z}, \qquad T_2 = T_1,$$

$$\Gamma_3 \qquad \lambda_1 \frac{\partial T_1}{\partial z} = \lambda_g \frac{\partial T_g}{\partial z}, \qquad T_1 = T_g,$$

$$\Gamma_4 \qquad \alpha_2 (T_{ea} - T) = \lambda_g \frac{\partial T_g}{\partial z},$$

Initial conditions for the equations:

$$T_i\Big|_{t=0} = T_{i0}, \qquad I = g, 1\text{-}3)$$

where T_i, ρ_i, c_i, λ_i - temperature, density, heat capacity, thermal conductivity (g - air layer, 1 – forest fuel layer, 2 - upper soil layer, 3 - lower soil layer); α_1 is the heat transfer coefficient; α_2 is the heat transfer coefficient; z is the spatial coordinate. t is the time coordinate. The es, ea, 0 are the indices correspond to the environmental parameters in the depth of the soil, the air, and at the initial moment of time.

The following initial data were used in the numerical simulation: ρ_1=1330 kg/m^3; ρ_2=1070 kg/m^3; ρ_3=500 kg/m^3; ρ^4=0.03 kg/m^3; c_1=801 J/(kg·K); c_2=976 J/(kg·K); c_3=1400 J/(kg·K); c_4=1200 J/(kg·K); λ_1=0.84 W/(m·K); λ_2= 0.5 W/(m·K); λ_3= 0.102 W/(m·K); λ_4=0.1 W/(m·K); α_1= 20 W/(m^2·K); α_2= 80 W/(m^2·K).

All foci were simulated by setting in the computational region of the high temperature zone. The temperature of the external source of exposure, characteristic of the combustion of forest fuels, was set. In the process of exposure, there was no additional heat release from the chemical reaction of oxidation of the gaseous pyrolysis products, that is, an estimate was made from below (the minimal effect of a forest fire on the surface soil layers).

RESULTS AND DISCUSSION

The influence of the ignition source on the soil layer was studied using a mathematical model. In fig. 1. and fig. 2. shows the temperature distribution in the system “clay-organic layer-organic matter – forest fuel-air”, respectively, after 5 and 20 minutes of activity of the forest fire.

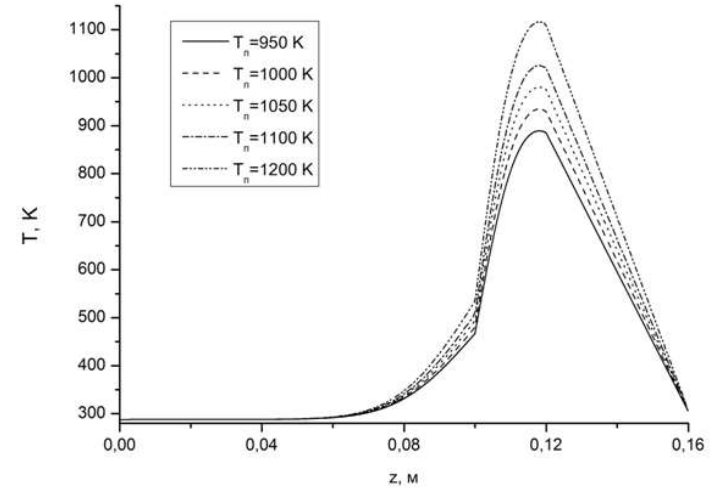

Fig. 1. Temperature distribution in the system “clay-organic layer-forest fuel-air” after 5 minutes of activity of the fire

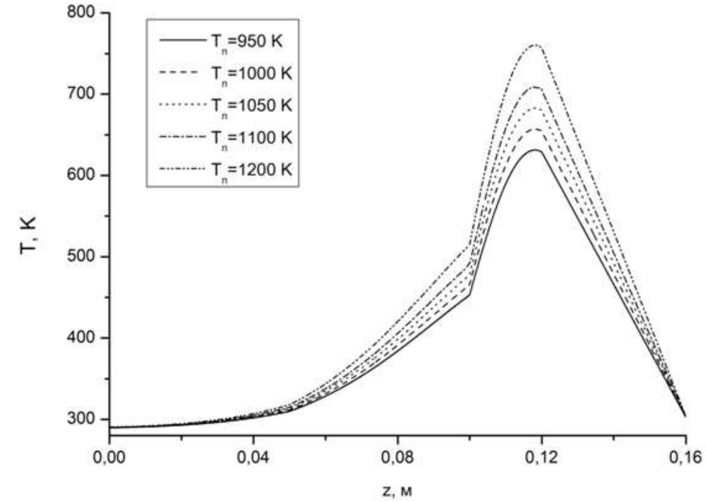

Fig. 2. Temperature distribution in the system “clay-organic layer-forest fuel-air” after 20 minutes of activity of the fire

As can be seen from fig. 1, with such a short-term effect of the focus of a forest fire, significant differences in soil temperature are noticeable at a depth of 1-1.5 cm from the interface of the “soil-forest fuel” media. In the soil in a layer rich in organic matter at a depth of 1.5-1.7 cm, the medium warms up above 100 ° C and high-temperature evaporation of the soil moisture is possible. In the upper centimeter layer of the soil, its charring and pyrolysis of vegetation residues is possible.

According to Fig. 2, with a longer exposure to the focus of a forest fire, significant differences in soil temperature are noticeable at a depth of 4–5 cm from the interface of the "soil-forest fuel" medium. The medium also warms up above 100 °C and high-temperature evaporation of soil moisture is possible in the soil in a layer rich in organic matter at a depth of 2-2.5 cm. Its charring and intensive pyrolysis of plant residues is possible in the upper two-centimeter layer of the soil.

In fig. 3 and fig. 4 shows the dependence of soil temperature at a depth of 1 cm from time for two different periods of exposure to forest fires.

Analysis of the data presented in Fig. 3 and fig. 4, allows us to conclude that the significant effects of various forest fires on soils at a depth of 1 cm. In this subsurface layer, zones of inert heating, evaporation of soil moisture, and thermal decomposition of plant residues and soil organic matter can be distinguished according to temperature. For example, a difference of 30 K is observed for the most intense focus of a forest fire (fire storm). It is clear that both short-term exposure and a long burning process will lead to changes in the soil.

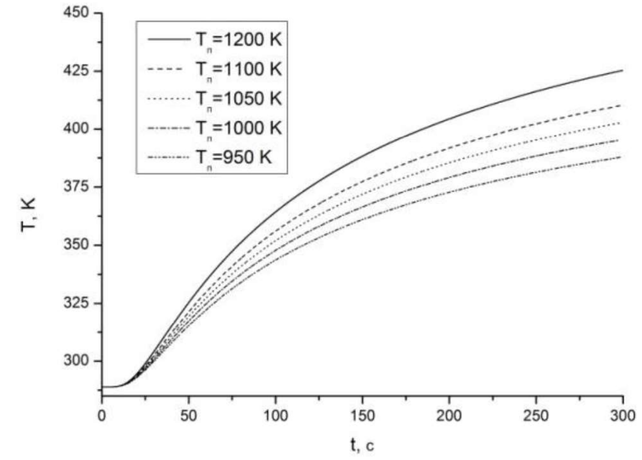

Fig. 3. Dependence of soil temperature at a depth of 1 cm from time (exposure time 5 minutes)

The initial values of the surface temperature of the soil, ambient air, and soil layers were set on the basis of reference data. In the future, it is possible to use more detailed mathematical models for estimating undisturbed temperature profiles in the soil along the vertical coordinate.

A comparative analysis of the algorithm was carried out using experimental data on the inert heating of the soil layer with an electric heating element. The heating was carried out with a maximum temperature of 130 °C in order to avoid the influence of the thermal decomposition of organic matter, which was part of the model soil. The starting point of temperature is from ambient to T_{max} = 130 °C.

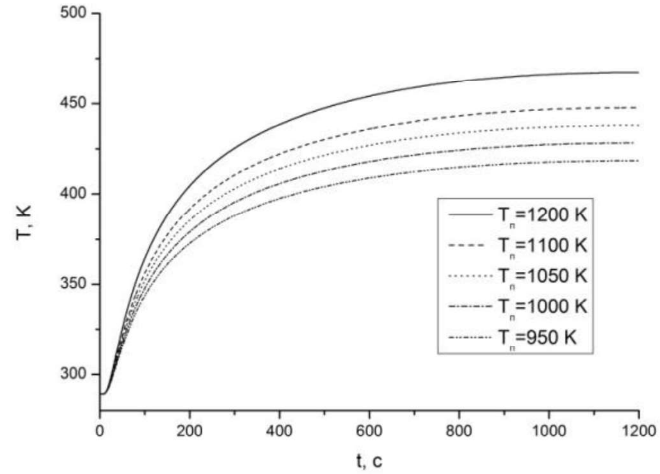

Fig. 4. Dependence of soil temperature at a depth of 1 cm from time (exposure time 20 minutes)

In the numerical calculation, two options were used: a) a linear increase in temperature during the warm-up period of the electric element (Fig. 5); b) the averaged value of the heater temperature in the calculation process (Fig. 6). An experimental stand was created that included a group of thermocouples embedded in the soil layer. Thermocouples through the controller were connected to a personal computer on which information processing was carried out using the LabView software.

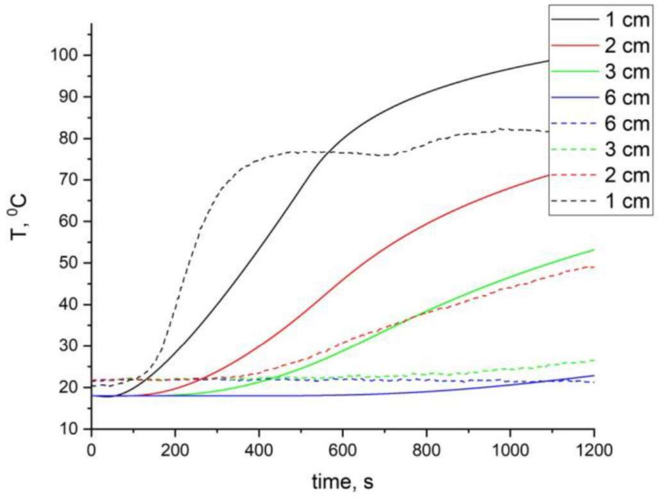

Fig. 5. Temperature curves in the soil layer at different depths depending on time (gradual heating - linear approximation): solid line - numerical calculation; dotted line – experiment

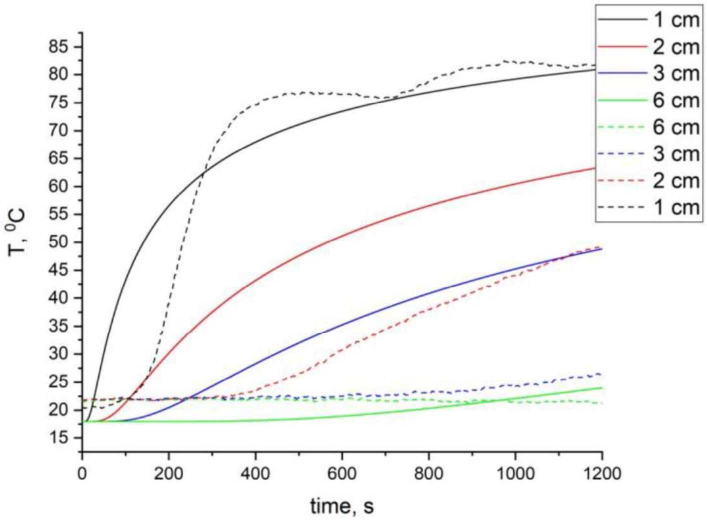

Fig. 6. Temperature curves in the soil layer at different depths depending on time (time-averaged temperature of the heater): solid line - numerical calculation; dotted line – experiment

CONCLUSION

For the first time, the simplest one-dimensional mathematical model for assessing the influence of the thermal regimes of forest fires on the near-surface soil layers is presented. Considered a two-layer soil structure. It has been established that significant changes in soil temperature occur only in a layer rich in organic matter. What will lead to a significant impact on the functioning of microbiogeocenoses.

The temperature distribution in the system "clay-layer-organic-layer-forest fuel-layer-air" is obtained for various types of forest fires and at different points in time. The obtained data can be used to assess the boundaries of the influence of forest fires on the functioning of microbiogeocenoses.

It should be noted that for a number of scenarios for calculating the temperature in the soil layer, satisfactory agreement between the calculated curves and the averaged values of temperature obtained in the experiment was obtained. It should be noted that for thermocouples at a depth of 2, 3, 6 centimeters, curves with a large deviation from the average were obtained. Statistical analysis showed that for thermocouples at a depth of 2 and 3 centimeters confidence intervals intersect. Basically, overestimated temperatures were obtained by numerical calculation. Good agreement between the results of numerical simulation and experimental data was obtained at a depth of 1 cm for the scenario of averaged heater temperature. This suggests that the model needs further improvement, namely, it is necessary to take into account the thermal decomposition of organic matter and the evaporation of moisture from the soil layer with inert heating of the soil layer. However, this model can be used for a preliminary estimate of the temperature at a certain depth of the soil when exposed to a source of forest fire.

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