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Contents

Mathematical and Computer Model of the Tree Crown Ignition Process from a Mobile Grassroots Fire

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Abstract. Forest fires cause great damage to the environment and are difficult to predict and eliminate. Mathematical models of temperature regimes of forest fires can create a scientific basis for improving the effectiveness of firefighting measures. The study of fire propagation processes and temperature regimes during a fire is an urgent task that many researchers are engaged in. The processes of heat exchange in the process of fire are very complex and include many factors. For this reason, they are difficult to model. The equations of heat transfer processes themselves are also difficult to solve and obtain analytical solutions.The aim of this work is to create a mathematical model of the ignition of a needle from the flame of a moving ground fire. The solution of the set tasks was carried out by the method of direct integration.The model of the process of heating the lower part of the tree crown due to the moving grass fire described in this paper has the advantage that it is based on mathematical calculations that can be easily performed using the mathematical software package Maple. The program in the Maple package is offered, which, depending on the input data: the size of the fire area, the speed of fire spread, the distance from the ground to the bottom of the crown, calculates the air temperature. These results can be used to calculate and assess the operational situation during forest fires.

Keywords: Convective heat transfer · Flash point · Flame of a moving ground fire · Forest fire · Modeling of forest fires

1 Introduction

Forest fires, which occur in most countries of the world, cause irreparable damage to the environment and the economy. Every year, devastating forest fires break out in Spain, Portugal, Australia, Greece, the United States, and other countries. Due to the sharp warming of the planet and climate change, the scale of forest fires, the speed of their spread, and the damage they cause is catastrophic. For example, in July 2018 - a fire in Greece, killed about a hundred people and more

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than 180 victims [1]; in September 2020 - the area of forest fire in California (USA) was more than 800 thousand hectares, more than 3300 buildings were destroyed, 14000 firefighters were involved in the elimination of this fire [2]; in August 2021 - forest fires had flared up and become catastrophic, uncontrollable in Greece, Turkey, and other Mediterranean countries [3]; in January 2022 - a devastating catastrophic forest fire in Colorado (USA) destroyed several hundred buildings in just a couple of hours. Unfortunately, Ukraine is no exception [5]. Only since 2022, about 90 forest fires with an area of more than 400 hectares have been eliminated in Ukraine [4].

Under such conditions, the study of the processes of forest fires becomes very relevant. To effectively organize the processes of forest fire prevention, by anticipating possible directions of its spread and effective organization of forest fire fighting, it is necessary to understand the course of forest fire and identify natural and anthropogenic factors that have the most significant impact on its development and spreading. The experimental study of forest fire on a physical model is expensive and almost unrealistic. The most appropriate is the mathematical modeling of the development process and spread of forest fires, to study them. Which in turn cannot be done without using the capabilities of modern information technology.

2 Literature Review

In scientific periodicals, we find thousands of publications related to this issue. Each of these publications contributes to the prevention of this scourge. Many works are devoted to computer modeling of fire contours and fire propagation [6,7,10,11,16,17]. In particular, in [6] the author considers each point of the forest fire contour in space separately, regardless of neighboring points, however, such a model for constructing the movement of the forest fire contour can be reliable only when describing convex contours. In [17] the author uses the method of predicting the shape of the forest fire contour, which is based on the construction of an extrapolated image of a certain stage of forest fire development using extrapolation formulas and available images of previous stages of its development. However, over time, the shape of the forest fire circuit completely "forgets" the previous form of ignition. In [7] the author investigates the relationship between the rate of propagation of the forest fire contour and the effects of flame geometry and slope. The relationships between flame geometry and Froude's convection number have also been studied in [15,18,19]. In particular, experimental testing of these models was carried out in [21–23].

The most well-known simulation models of forest fires are Rothermel [8] and Wang Zhengfei [13,25]. However, for proper operation, they require a large number of input parameters, which, as a rule, in the conditions of rapid large-scale forest fires are absent. In addition, the Zhengfei simulation model [25] is valid only when modeling the spread of forest fire in areas where the terrain has no slope of more than 60^0. Particular attention should be paid to works on mathematical modeling of heat transfer and heat and mass transfer processes during forest fires [9,12,20,24]. In particular, in [12] a mathematical model of the process of heating the needle due to radiant heat radiation from the surface in the form of a rectangle can set the time of its heating to the autoignition temperature. In [9], a mathematical model for predicting the spread of the landscape forest fire contour was developed, taking into account three types of heat exchange: heat conduction, convective heat exchange, and heat radiation. It should be noted that a number of the above models meet the requirements for validation of forest fire spreading models specified in [14].

Most of the above models require a large number of input parameters that are not always available and perform complex mathematical calculations. Obviously, without using modern integrated software systems and software packages to automate mathematical calculations they are unusable.

In addition, in the conditions of ephemerality and uncertainty of the development of large-scale forest fire, the head of forest fire extinguishing, to begin the process of forest fire extinguishing it is necessary to obtain at least its general characteristics as soon as possible. Therefore, in order to optimize the time of obtaining a model of forest fire, we neglect a number of input parameters that can be specified in the process of forest fire and build a simplified mathematical model of burning needles on tree canopies from the flames of mobile grassland fire using Maple.

3 Problem Statement

Many scientific publications are devoted to the problems of modeling the spread of fire. It is necessary to single out works devoted to modeling of fire torches, construction of simulation models of fires. Calculation of temperature regimes during an open fire is associated with great technical difficulties. Such models need to take into account a large number of parameters and conditions and three types of heat transfer: thermal conductivity, convection, radiation. As a result, the mathematical model consists of differential equations in partial derivatives of higher orders. For such models it is almost impossible to obtain solutions in analytical form. In addition, such models are very difficult to algorithmize and program. We propose to consider a model based on the laws of radiation without taking into account convective heat transfer. This model is much simpler because it is described by a first-order differential equation.

The aim of our study is to create a mathematical model of heat transfer during a ground fire, which can be used to set the air temperature at the desired height depending on the time, speed of fire and the size of the fire area. To create this model, we rely on the known equations of the laws of heat transfer in the process of heating the surface of a certain area to a certain temperature. In our model, we want to take into account that the area of the fire is moving at a constant speed. For convenience of calculations, we believe that the fire area has a rectangular shape. In our model, we introduce a coordinate system that allows you to take into account the dynamics of the fire at a constant speed. In the process of modeling, we expect the opportunity to obtain the dependence of temperature on time. The differential equation includes the angular irradiation coefficient, which is also a function of time. In this situation, there are difficulties with integration. As a result, we obtain the solution of the differential equation in implicit form. Modern software allows you to perform calculations and get point results in the required number with a high speed of calculations. We have created an algorithm, which is later presented by pseudocode in our article. We performed calculations using the Maple mathematical package. In the first stage, integration steels are calculated for each value of the distance from the fire to the lower part of the crown, in the second stage, irradiation coefficients and temperature values are calculated.

4 Matherial and Methods

Consider the theoretical foundations of our model. To heat some surface with area S with temperature T, irradiated from the surface of the rectangle of constant temperature T_1 (consider the surface flat) during time dt, the amount of heat will be spent

$$Q = \sigma\varepsilon(T_1^4 - T^4) \tag{1}$$

From another point of view, heating this surface by a magnitude dT determined by the formula

$$Q = cmdT \tag{2}$$

where m is the weight of surface, unit of measurement - kilogram σ is the Stefan-Boltzmann constant, ε is the emissivity, ψ is the angular irradiation coefficient (by Lambert's law), c is the specific heat, $\frac{Joule}{kg*K}$. We assume that all the heat received by the radiation will be spent on heating the surface. Equate the right parts of formulas (1) and (2). We obtain a differential equation:

$$cmdT = \sigma\varepsilon(T_1^4 - T^4)\psi(t)Sdt. \tag{3}$$

This equation describes the process of heating the surface to temperature $T = T(t)$ over time t.

The initial condition for this equation is the condition:

$$T(0) = T_0$$

The radiation coefficient ψ for an element of an area dS and a flat rectangle parallel to it , if the normal to the element passes through the angle of this rectangle is determined by the formula (Fig. 1)

$$\psi = \frac{1}{2\pi}\left(\frac{a}{\sqrt{a^2+r^2}}\arctan\frac{b}{\sqrt{a^2+r^2}} + \frac{b}{\sqrt{b^2+r^2}}\arctan\frac{a}{\sqrt{b^2+r^2}}\right) \tag{4}$$

For the case if the irradiated area dS is located opposite the center of the rectangle, the irradiation coefficient is determined by the formula

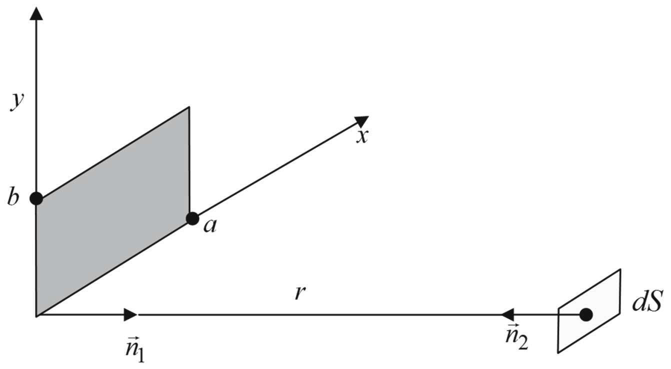

Fig. 1. Irradiation of a stationary surface

$$\psi = \frac{2}{\pi}\left(\frac{a}{\sqrt{a^2+4r^2}}\arctan\frac{b}{\sqrt{a^2+4r^2}}+\frac{b}{\sqrt{b^2+4r^2}}\arctan\frac{a}{\sqrt{b^2+4r^2}}\right) \tag{5}$$

For the case if the irradiated area dS is located opposite the point of the rectangle, which has coordinates $(x;y)$, the irradiation coefficient is determined by the formula

$$\psi = \frac{2}{\pi}\left(\frac{y}{\sqrt{y^2+4r^2}}\arctan\frac{x}{\sqrt{y^2+r^2}}+\frac{x}{\sqrt{x^2+y^2}}\arctan\frac{y}{\sqrt{x^2+r^2}}\right)$$

$$+\frac{1}{2\pi}\left(\frac{y}{\sqrt{y^2+r^2}}\arctan\frac{b-x}{\sqrt{y^2+r^2}}+\frac{b-x}{\sqrt{(b-x)^2+y^2}}\arctan\frac{y}{\sqrt{(b-x)^2+r^2}}\right)$$

$$+\frac{1}{2\pi}\left(\frac{a-y}{\sqrt{(a-y)^2+r^2}}\arctan\frac{x}{\sqrt{(a-y)^2+r^2}}+\frac{x}{\sqrt{x^2+r^2}}\arctan\frac{y}{\sqrt{x^2+r^2}}\right)$$

$$+\frac{1}{2\pi}\left(\frac{a-y}{\sqrt{(a-y)^2+r^2}}\arctan\frac{(b-x)}{\sqrt{(a-y)^2+r^2}}\right)$$

$$+\frac{1}{2\pi}\left(\frac{(b-x)}{\sqrt{(b-x)^2+r^2}}\arctan\frac{a-y}{\sqrt{(b-x)^2+r^2}}\right) \tag{6}$$

Consider a needle or leaf, which is at a height of r, m from the ground. The surface of a flame is considered to be a horizontal rectangle a, m long and d, m wide, moving at a constant speed $x = v(t - t_0)$ in a direction perpendicular to the leafes or needles. Heat exchange between the needle or leaf and the moving surface is carried out according to formula (5). If you choose a coordinate system so that the needle is projected on a straight line passing through the center of the rectangle, parallel to the width d and impose the condition that at the time $t = 0$ the moving surface is in position $-x$ (Fig. 2), then formula (5) will look like

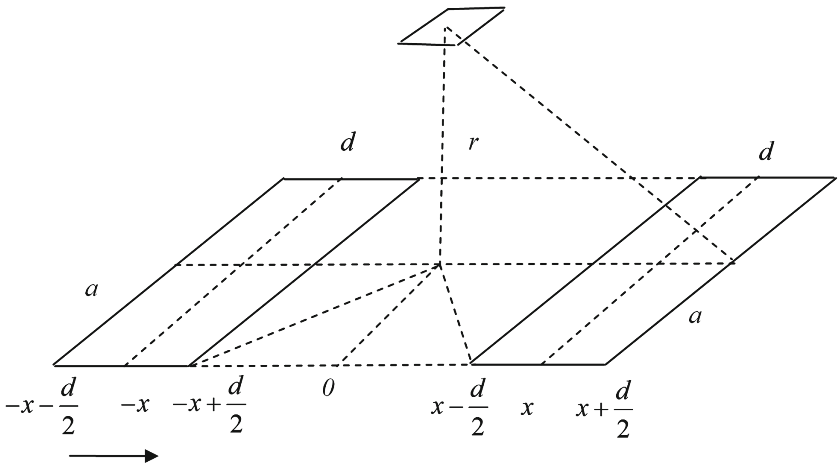

Fig. 2. Movable irradiation surface

$$\psi = \frac{1}{\pi}\frac{a}{\sqrt{a^2+4r^2}}\arctan\frac{2x+d}{\sqrt{a^2+4r^2}}$$
$$+\frac{1}{\pi}\frac{2x+d}{\sqrt{(2x+d)^2+4r^2}}\arctan\frac{a}{\sqrt{(2x+d)^2+4r^2}}$$
$$-\frac{1}{\pi}\frac{a}{\sqrt{a^2+4r^2}}\arctan\frac{2x-d}{\sqrt{a^2+4r^2}}$$
$$+\frac{1}{\pi}\frac{2x-d}{\sqrt{(2x-d)^2+4r^2}}\arctan\frac{a}{\sqrt{(2x-d)^2+4r^2}} \tag{7}$$

Substitute in (7) $x = vt$, we obtain

$$\psi(t) = \frac{1}{\pi}\frac{a}{\sqrt{a^2+4r^2}}\arctan\frac{2vt+d}{\sqrt{a^2+4r^2}}$$
$$+\frac{1}{\pi}\frac{2vt+d}{\sqrt{(2vt+d)^2+4r^2}}\arctan\frac{a}{\sqrt{(2vt+d)^2+4r^2}}$$
$$-\frac{1}{\pi}\frac{a}{\sqrt{a^2+4r^2}}\arctan\frac{2vt-d}{\sqrt{a^2+4r^2}}$$
$$+\frac{1}{\pi}\frac{2vt-d}{\sqrt{(2vt-d)^2+4r^2}}\arctan\frac{a}{\sqrt{(2vt-d)^2+4r^2}} \tag{8}$$

In Eq. (3), separate the variables and integrate both parts of equation. As a result, we obtain

$$\frac{cm}{S\sigma\varepsilon}\int\frac{dT}{T_1^4-T^4} = \int\psi(t)dt \tag{9}$$

Using the method of integration by parts, we obtain the expression for the right part (9):

$$\Psi(t) = \int \psi(t)dt =$$

$$= \frac{a}{2v\pi}\left(\frac{2vt+d}{\sqrt{a^2+4r^2}}\arctan\frac{2vt+d}{\sqrt{a^2+4r^2}} - \frac{1}{2}\ln\left(1+\frac{(2vt+d)^2}{a^2+4r^2}\right)\right)$$
$$+\frac{1}{2v\pi}\sqrt{(2vt+d)^2+4r^2}\arctan\frac{a}{\sqrt{(2vt+d)^2+4r^2}}$$
$$+\frac{1}{2v\pi}\frac{a}{2}\ln((2vt+d)^2+4r^2+a^2)$$
$$+\frac{a}{2v\pi}\frac{2vt-d}{\sqrt{a^2+4r^2}}\arctan\frac{2vt-d}{\sqrt{a^2+4r^2}} - \frac{a}{4v\pi}\ln\left(1+\frac{(2vt-d)^2}{a^2+4r^2}\right)$$
$$+\frac{1}{2v\pi}\sqrt{(2vt-d)^2+4r^2}\arctan\frac{a}{\sqrt{(2vt-d)^2+4r^2}}$$
$$+\frac{a}{4v\pi}\ln((2vt-d)^2+4r^2+a^2)) \tag{10}$$

After direct integration of the left part of formula (9) we obtain

$$\int\frac{dT}{T_1^4-T^4} = \frac{1}{4T_1^3}\left(\ln\left|\frac{T_1+T}{T_1-T}\right| + 2\arctan\frac{T}{T_1}\right) + C \tag{11}$$

Thus we obtain the analytical expression of the general integral of the differential equation, which describes the process of heat transfer between the needles and the moving surface of the radiation.

$$\frac{cm}{S\sigma\varepsilon}\frac{1}{4T_1^3}\left(\ln\left|\frac{T_1+T}{T_1-T}\right| + 2\arctan\frac{T}{T_1}\right) = \psi(t) + C \tag{12}$$

Equation (12) is transcendent. To find the approximate solution, we decompose the left-hand side of this equation into the Taylor series.

$$\ln\left|\frac{T_1+T}{T_1-T}\right| + 2\arctan\frac{T}{T_1} = \frac{2T_1}{T-T_1} - \frac{2T_1^2}{(T-T_1)^2} + \frac{4T_1^3}{3(T-T_1)^3} + \frac{2T}{T_1} - \frac{T^3}{3T_1^3}$$

To find the integration constant, we substitute the initial conditions and input data. After substituting the constant in Eq. (12) we can find the value of temperature. Finally, the equation for finding the temperature has the form:

$$\frac{2T_1}{T-T_1} - \frac{2T_1^2}{(T-T_1)^2} + \frac{4T_1^3}{3(T-T_1)^3} + \frac{2T}{T_1} - \frac{T^3}{3T_1^3} = \psi(t) + C \tag{13}$$

5 Experiment, Results and Discussion

The model of temperature regimes of the lower part of the tree crown created by us has an implicit analytical solution given in formula (12). Dependence (12) is a transcendental function with respect to the variable T. We have solved this problem by decomposing the left-hand side of Eq. (12) into the Taylor series. As a result of such replacement the accuracy of the solution is lost. But the advantage is that the resulting equation is an algebraic equation of the third degree. Such equations can be solved quickly with the help of application mathematical packages that are publicly available. For this reason, the Maple software package was used to find the roots of this equation. Based on it, a program was created to calculate the integration constant and find the temperature of the needles or leaves of the tree depending on the distance from the soil surface to the bottom of the crown. The program takes into account the possibility of correcting the speed of fire, the size of the fire area, the distance from the soil surface to the bottom of the crown. The advantage of this method is the high speed of calculations, the availability of software. The input data to the problem are shown in Table 1. The flame temperature of the moving area is taken $T_1 = 900\,\mathrm{K}$. This is an average that can be replaced with another value if necessary. Assume that the ambient temperature is $T_0 = 293\,\mathrm{K}$. The program provides the ability to change the size of the fire zone and the speed at which it spreads. The speed of ground fire propagation, which is $v = 0,004$ meters per second, is taken for calculations. In addition, we have created an algorithm for calculating the temperature regime. Presented below Algorithm 1 describes the stepwise procedure of temperature calculations.

Table 1. The input data to the problem

No.	Abbr.	Assentiality	Quantity	Dimension
1	a	The width of the fire area	2	meters
2	d	The lendth of the fire area	2	meters
3	r	The height of the lower part of the tree crown	varies from 2 to 40	meters
4	v	Speed of fire spread	$0,004$	m/c
5	c	Specific heat	1172	$\frac{Joule}{kg \cdot K}$
6	T_0	Embient temperature	293	K
7	T_1	Flame temperature	900	K
8	m	Mass of a tree leaf	$0,062 \cdot 10^{-3}$	kg
9	ε	Emissivity	$0,7$	
10	σ	The Stefan - Boltzman constant	$5,67$	$\frac{Vt}{m^2 \cdot K^4}$
11	t	time	$[0; t_{max}]$	s

Algorithm 1: Calculation of the temperature of the lower part of the crown

Initialization:
calculate: calculate the integration constants C;
calculate the radiation coefficients $\psi_k(t)$;
create an array of temperatures T;
set: iteration counter r-the height of the lower part of the tree crown r;
iteration step of counter r $step1 = 4$
iteration counter k, iteration step of counter k $step2 = 16$
the size of the fire area a, d;
speed of fire spread v;
specific heat c;
embient temperature T_0;
flame temperature T_1;
mass of a tree leaf m;
emissivity ε;
the Stefan - Boltzman constant σ;
$a, d, v, step1, step2, T_0$ - set of input parameters, can be changed by the user, taking into account the operational situation on the fire
while $r \leq r_{max}$ **do**
  calculate the integration constant C
  while $k \leq t_{max}$ **do**
    Calculate the angular irradiation coefficient $\psi_k(t)$;
    Calculate the temperature $T_k(t)$
    $k = k + step2$;
  end
  $r = r + step1$;
end
Return array of temperatures T.

Table 2. The results of the calculation of the integration constants

r	2	6	10	14	18	22
C	417,99	559,68	637,78	690,44	730,06	761,81

Table 3. Dependence of crown temperature on time for different distances from the soil surface

T	t, c										
	0	16	32	48	64	80	96	112	128	144	160
$r = 2$	909.78	909.79	909.78	909.77	909.76	909.74	909.72	909.70	909.68	909.66	909.63
$r = 6$	905.13	905.13	905.13	905.13	905.13	905.12	905.12	905.12	905.12	905.12	905.12
$r = 10$	904.91	904.91	904.91	904.91	904.91	904.91	904.91	904.91	904.91	904.91	904.90
$r = 14$	904.78	904.78	904.78	904.78	904.78	904.78	904.78	904.78	904.78	904.78	904.78
$r = 18$	904.69	904.69	904.69	904.69	904.69	904.69	904.69	904.69	904.69	904.69	904.69
$r = 22$	904.63	904.63	904.63	904.63	904.63	904.63	904.63	904.63	904.63	904.63	904.63

The results of the calculation of the integration constants for the corresponding values of the crown height are shown in Table 2. The dependence of the temperature of the lower part of the tree crown on time is also shown in Table 3. The obtained temperature indicators indicate that due to the mobile fire the lower part of the tree crown heats up to the autoignition temperature. Another important feature is the observed decrease in temperature by 4 K in the transition from a height of 2 m to a height of 6 m from the soil surface. At transition from height of 6 m to height of 10 m temperature decreases only on 1 K. From a height of 10 m to a height of 22 m, the temperature remains almost stable and is 904 K.

6 Conclusions

The study of fire propagation processes and temperature regimes during a fire is an urgent task that many researchers are engaged in. The processes of heat exchange in the process of fire are very complex and include many factors. For this reason, they are difficult to model. The equations of heat transfer processes themselves are also difficult to solve and obtain analytical solutions. The model of calculation of temperature regimes of the lower part of the tree crown during a grassland fire proposed in our work is based on the first-order differential equation, the solution of which is obtained analytically. The calculation algorithm created by us consists of two nested cycles, on the basis of which the temperature array of the lower part of the crown is formed. The advantage of our model is that it is algorithmic and is available for programming the necessary calculations. The program in the Maple package is offered, which, depending on the input data: the size of the fire area, the speed of fire spread, the distance from the ground to the bottom of the crown, calculates the air temperature. According to the results of modeling with input data: the flame temperature of the moving area $T_1 = 900\,\mathrm{K}$, ambient temperature $T_0 = 293\,\mathrm{K}$, the speed of ground fire propagation $v = 0,004$ m/s, it was found that the temperature at the bottom of the crown varies from 905 K to 910 K. The model allows calculations with any input data.The advantage of our model is the possibility of primary operational calculation of temperature regimes. The user enters the input data and the program gives the desired result. These results can be used to calculate and assess the operational situation during forest fires.

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