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MODELING OF FIRE SUPPRESSION IN THE ECOLOGICAL SYSTEM OF TREES AND SHRUBS

Annotation. *This work presents an approach to mathematical modeling of directional suppression of fires in the ecosystem of trees and shrubs. It is taken into account that for effective extinguishing of fire in the natural ecosystem is necessary to ensure a uniform and strong impact of dispersed flow over the entire area of the hearth burning. The presented model can be used as a baseline when planning measures of prevention, localization and liquidation of fires in natural ecosystems near industrial centers. This approach will prevent the development of fire and environmental pollution by combustion products.*
Key words*: ecosystem, forest, fire, flow, model, process.*

Introduction

All over the world from fires in natural ecosystems at least 50% of the annual growth of trees burns on average. After a fire not earlier than 30 - 60 years is growing less valuable forest, swamps are formed, fauna dies – the whole region, where there was a forest fire irreparable environmental damage is caused. With the industrial and cultural development of forests in the countries by lumber companies, tourists, and vacationers, a number of forest fires, their speed of development, the scale, losses and environmental damage from these fires increase.

This topic is particularly relevant for the territory of the Luhansk region. In the region, there are small forest plantations of anthropogenic origin. In the agricultural part of the Luhansk region is deciduous trees and shrubs. In the industrial part of the Luhansk region is pine plantations.

The territory of Luhansk region is characterized by arid climate in summer, the typical temperature spikes to 40°C. Near industrial centers, it is observed increase in air temperature connected with the work of vehicles and industrial enterprises.

According to statistics, forest and Prairie fires in summer are registered by employees of the State service of emergencies of Ukraine in Luhansk area 10-12 times a day. As a rule, this is fire forest litter, dry grass in the steppe and along the roads.

However, the most significant environmental and economic damage are forest fires around Severodonetsk, in the Kreminskyi forests, in forest plantations of Lisichansk. These are the cities, where the enterprises of chemical and coal mining are situated. Green spaces are a barrier to trap harmful substances released by enterprises. Naturally, when it is a forest fire all of these substances are released into the air from combustion products, causing huge damage to people and the environment.

Purpose of the work: to present one of approaches to modeling the process of extinguishing fires in the ecological systems of trees and shrubs that have been planted by man around industrial cities.

Tasks of the work:

a) to consider the features of the spread of fire in the ecosystem of trees and shrubs;

b) to represent a model of flame spread among the trees;

c) to create a model of the process of fire extinguishing with the physical and chemical properties of the environment.

Questions of ecological safety of technogenic loaded areas and approaches for the localization and liquidation of fires in the natural environment is considered to Dovhyi S.O. [1], Trofymchuk A. N. [2-3], Yakovlev E. A. [3], Zakhmatov V. D. [4], Snytyuk V. E. [5] and others [6].

1. Features of the spread of fires in the ecological system of trees and shrubs

Planting trees and shrubs, which is forest, forest plantation, forest zone, park, square, is a special ecosystem. This ecosystem consists of several tiers and is a community of closely related elements of animate and inanimate nature (biota). The forest biota includes vegetation, animals, and microorganisms. Fire of the ecological system of trees and shrubs affects all components of animate and inanimate nature, because it is a complex of combustion system, consisting of a combination of burning wood - trunks, branches, stumps, foliage on trees and on the ground with the participation of oxygen and other chemical elements that are found on the leaves, wood, and soil.

Wood is inhomogeneous and anisotropic combustible material, flammable ability of which is strongly depends on the structure and therefore unequal in different directions. Wood is a complex mixture of natural polymers of high relative molecular mass: cellulose 50%, helicella 25%, lignin 25% and moisture up to 85%. The mass fraction of these components and moisture varies depending on tree species, time of year and weather.

Due to the fibrous structure of wood, its thermal conductivity in the direction parallel to the fibers is approximately two times more thermal conductivity in the direction perpendicular to the fibers. The difference in the gas permeability reaches much larger values, respectively, to 1000:1. Combustible volatile products are pairs of sublimation wood, (are the gas phase of the combustion process and are formed directly under the surface not covered by the fire of the part wood) are easier evaporated through the channels along the fibers than through the thin top layer of wood.

The evaporation process may have a different intensity and occurs mainly during heating to the temperature interval 200-250°C, after which most of the volatile products from a surface layer of wood has already evaporated and it starts charring the layer. Prolonged gradual heating process of sublimation ends at low temperatures up to 120°C and starts charring. At temperatures above 300°C, it begins the more intensive cracking of the surface layer of the wood, the result is heating and the process of sublimation of the deeper layers of wood begins. Already at a temperature T=300°C there is a process of rapid physical degradation with the appearance of weak cracks perpendicular to the fiber direction, which allows fuel pairs that were formed at the bottom warms layers of wood to go on set of cracks through the charred layer and burn on this layer and even in the layer. With increasing depth and intensity of combustion of the carbonaceous layer, the cracks will grow in length, width and depth, the surface of the burning material will be splitting and cracking. Thus is formed a powerful condensed area with large reserves of heat, available even after a long time of the downed flame to restore the combustion process.

Flammability of wood depends on acting on her heat flow. The linear burning rate of wood is 0.6 mm/min. The burning rate is not constant, and changes considerably depending on the heat flow formula,

$$\omega_n = 2{,}2 \times 10^{-2} \mathrm{I}, \tag{1}$$

where I is expressed in KW/m^2. During fires of the piles of wood and fallen forest, the local temperature in some points can reach 1100°C; the corresponding radiation of a black body is 200 KW/m2, which may cause an increase in the rate of burning of wood to 4.4 mm/min. The burning speed depends on the thickness of the burning fragment of a tree – a trunk, a branch. A relatively thin layer under the burning surface of combustible material is exposed to thermal effects. Large burning rate will be observed for thin samples, provided that the heat sink from the back side of a burning fragment of wood will not be high enough. Thick fragments of branches of the trunks are hard to flame and slower to burn due to intense heat sink into the wood, especially if the barrel at least partially retained moisture and didn't dry. Thick wooden pieces can't burn in isolated conditions from the air flow - if the flame covers them from all sides, on the contrary, in this case, thin wood chips and branches are easily ignited and burn quickly because the intensity of the heat sink will be minimal. Therefore, in the initial stage of combustion is more difficult to extinguish thin branches, especially their plexus and a handful of wood chips, shavings, respectively, when reaching a good flare-UPS that is, formation of the developed warm layer it is harder to extinguish thick logs because of the large supply of heat accumulated in the thickness of the charred layer.

The most difficult cases for suppression are: the trunks of the trees with a rough surface with hollows and provigilonline stumps, the tangle of thick branches, trunks, modeled by the stack cell crossing rows of logs. The accumulation of the heat inside the stack and mutual transverse thermal radiation of burning surfaces greatly accelerates the buildup and the process of burning of thick timbers and logs. Therefore, stacks are used in experiments as a means of generating sustainable and self-renewable sources of fires, the burning rate of which is regulated by a number of parameters - thickness logs B, the number of rows in the stack N, the distance (of timbers) of logs from each other in each row S, the length of the logs L.

2. Model of flame spread among the trees

The mechanism of flame spread among plantings of trees includes radiative heat transfer before the flame front. The advancing flame front takes with the expression (2) the speed of flame propagation will be inversely proportional to the average density of the hearth:

$$V = \frac{q}{p_\Delta h} = \frac{\varepsilon\delta(T_F^4 - T_0^4)}{p_\Delta h} \tag{2}$$

However, this formula does not take into account all the important factors, such as humidity. The formula is correct enough, if some elements of combustible material is considered as thin. Another case examines a replacement density of the lesion within effective density, which takes into account the fact that until the arrival of the flame front, only the surface layers of each element are subjected to heat, and the practice shows that only localized areas of these layers heat up. In the ecosystem of trees and bushes, the fire spreads most quickly through the shrub, branches creeping along the ground or through the edge of the trees, where the average density is low and the elements of a solid combustible material is thin. Considerable speed of fire spread is possible in the drought conditions with low humidity. Such conditions are typical for pine forests that grow around Severodonetsk town, Luhanskaya region.

For the existence of stable combustion of the solid material the following conditions must be performed:

– combustible material in the combustion zone must be sufficiently porous (cracked) to ensure penetration of the oxidant (oxygen) to the mass of combustible material;

– the material in the process of thermal decomposition should give a solid carbonaceous residue, which ensures the fulfilment of the first condition;

– the combustion process needs to penetrate into the depth of the material, this creates a condensed combustion zone that is a high temperature surface layer, in which self-heating processes are brightly manifested that causes a wave of smoldering slow burning, slowly spreading inside the combustible material to the inner layers by contact heat transfer.

As a result of such processes inside a condensed zone – the high temperature surface layer of a solid material a self-combustion reaction is formed, a stock removal is accumulated, which provides the ignition even after multiple external re-appearance of downed flame and isolation from the oxygen for a long time up to several hours.

The process of burning charred surface provides the flow of heat necessary for the process of thermal decomposition of the underlying layer of combustible material. For successful dissemination of this process it is required sequential removal of non-combustible high temperature of the solid residue and gaseous products of combustion – the smoke from the active burning zones that will expose a fresh carbon layer, which immediately ignites on contact with the oxygen. The presence of intensive surface oxidation process inside the cracks of the porous material in zones of cracking and pyrolysis is the condition for a sustained process of combustion of a solid material.

3. Modeling of the process of fire extinguishing taking into account the physico-chemical properties of the environment

For the process of combustion of is typical a strong dependence of the rate of the chemical reaction on the physico-chemical properties, aggregate state, temperatures of combustible substances and oxidizer, and the ignition conditions. All of these factors have well-defined critical value, when reaching at least one of them, the process of burning stops. For the combustion reaction it’s typical critical modes and abrupt changes in burning rate at relatively small changes of combustion system parameters. Termination of a continuous process of interaction between counter flows of fuel, oxidizer and heat flux in the charred K-zone – the destruction of this zone happened for a small period throughout the whole combustion system is a condition for effective extinguishing. At this undeveloped stage of combustion – ignition of solid material after the cessation of exothermic chemical reactions, there are processes of self-destruction plasma and condensed (K) combustion zones and dispersion of combustion products by means of intensive heat and mass transfer with the environment.

Until the formation of a stable charred zone with significant reserves of heat, the hearth recently ignited solid material easy to put out. This requires to reduce by 15-20% the heat flux to the surface of the solid combustible material, where a charred zone is formed. The transition from ignition to stationary combustion is characterized by a large heat absorption for the formation of surface, high temperature K-zone layer and then a rapid increase of the reaction rate with relatively small further changes in temperature and the heat content of the burning material.

For the most effective extinguishing of the hot solid materials one can create intense gas-dispersed flow directed mainly into the surface layer of hot material and providing an even saturation of this layer with finely atomized fire extinguishing agent.

Let's consider the advantages of directional quenching in comparison with traditionally used ways of applying extinguishing agent to the whole fire burning. For this, let's imagine numerical evidence of the benefits of the directional fire exposure on certain zone of hearth burning, which is the foundation of this burning process. In the case of type A fires, such zone is condensing (if-zone), that is porous, cracked, charred, molten layer of the solid combustible material. In any stage of development of the class A fires the destruction of the if-zone combined with cooling, inhibition or exception of material of this zone - the high temperature combustible particles from the oxygen is the only possible way of final extinguishing of class A fires. The destruction of all other zones - diffusion (D), plasma or smoke will not lead to the final extinguishing. If-zone can restore other zones and the process of combustion even during a long period of time after extinguishing all of the burning area at a constant distance from the installation of the extinguishing composition to the far border of the fire. In this case, the consumption of extinguishing agent must exceed a certain critical value:

$$F_0 \upsilon_0 > (F_0 \upsilon_0)_{\text{кр}} \tag{3}$$

where

F – required value of the contact surface area of the aggregate particles of the powdered fire-extinguishing composition with the burning of solid and combustible particles and their flammable vapors.

V_0 is the initial horizontal speed of the front of the solid phase (particles of the extinguishing composition).

Based on the flow of extinguishing agent the dependence of the magnitude of the surface area of the particles of the F_0 fire extinguishing composition from the speed of fire-extinguishing flow V can be obtained:

$$(F_0 v_0) = \frac{F_x}{D_0}(4|v_z|x_0 + u_x D_c)\ell \frac{\gamma(L-x)}{u_x} \tag{4}$$

In the expression (4) designation F_x, u_x, D_c, V_z, X_0, U_0 are the particle parameters of the fire extinguishing composition. Accordingly: the critical value of the area of the sum contact surface of the particles of the extinguishing agent with the zones hearth of fire; the current speed of the fire extinguishing stream at a distance X from the installation of the extinguishing substances; the averaging diffusion coefficient of the particles of the extinguishing composition at the moment of contact with the combustible material; the average absolute value of the vertical component of particle velocity; the range of penetration of particles of the fire extinguishing mixture in the combustion zone.

Also:

v_i – the initial (muzzle) velocity of the front fire-extinguishing thread;

u_x – vertical component of velocity of the gaseous products of combustion (smoke);

L – the distance from the far border hearth of the fire to the position of installation of the extinguishing composition;

γ – the time of radicals of a combustible substance generating.

For the implementation of the extinguish fire in the ecosystem of trees and shrubs it is necessary to ensure a uniform and strong impact of dispersed flow over the whole area of the hearth burning – that is, to provide that X>L. In this case, the following form gives the formula (4):

$$F_0 v_0 > F_{кр} \frac{4|v_z|x_0 + v_x D_c}{D_c} expO = \frac{F_x}{D_c}(4|v_z| + u_x D_c) \tag{5}$$

Subsequently, this model can be slightly simplified by expressing the mass of the fire extinguishing composition through the total surface area of its particles. This will allow to describe the surface of the hearth fire fighting through a potential of the spraying fire-extinguishing compositions.

However, presented model (5) gives a complete picture of the impact of extinguishing composition on the hearth burning and allows to design a stream of particles for aimed firefighting ignition in the ecosystem of trees and shrubs.

Conclusion

The fight against forest fires has long passed beyond the regional issues and turned into an acute political-economic problem for the state. On average, no more than 1-2% of the sprayed mass of extinguishing agent falls on the charred surface of the trees and cools the high-temperature layer, which is the foundation of a forest fire and a source of repeated firings. That is why the task of creating a focused dispersion stream to dense cover the largest possible area of fire is primary in the implementation of technologies for fire-fighting.

This work presents one of solutions of this problem. The presented model allows providing a uniform and strong impact of dispersed flow over the entire area of the hearth burning and can be used as a baseline when planning measures for prevention, localization and liquidation of fires in natural ecosystems near industrial centers. This approach will prevent the development of fire and environmental pollution by combustion products.

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