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DEVELOPMENT OF THE TECHNIQUE FOR RESTRICTING THE PROPAGATION OF FIRE IN NATURAL PEAT ECOSYSTEMS

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У результаті математичного моделювання теплових процесів у системі торфовий пласт – протипожежна перешкода виявлені залежності часу досягнення небезпечної температури торфового пласту від товщини перешкоди. Визначені параметри регресійних залежностей товщини перешкоди від часу, впродовж якого необхідно забезпечувати захист торфового пласту. Досліджено запропоновані перешкоди для локалізації торф'яних пожеж та захисту навколишніх об'єктів

Ключові слова: температура торф'яного пласту, мінеральна протипожежна перешкода, пожежна безпека торфу

В результате математического моделирования тепловых процессов в системе торфяной пласт – противопожарная преграда обнаружены зависимости времени достижения опасной температуры торфяного пласта от толщины препятствия. Определены параметры регрессионных зависимостей толщины преграды от времени, в течение которого необходимо обеспечивать защиту торфяного пласта. Исследованы предложенные препятствия для локализации торфяных пожаров и защиты окружающих объектов

Ключевые слова: температура торфяного пласта, минеральное противопожарное препятствие, пожарная безопасность торфа

1. Introduction

Peat fires occur in different countries of the world, in particular, the USA, Canada, Great Britain, Ukraine, Republic of Belarus, India, and others. When fighting such fires all over the planet, people are faced with the same problems. Peat burning is accompanied with a pollution of the environment. That is why the emissions from peat fires can become a significant environmental problem. As a rule, such fires are very large and need the utilization of a large amount of human and material resources.

The feature of the development of peat fires is the absence of open fire on the surface. Burning occurs at different depth and only sometimes the fire briefly breaks through from beneath the soil. A sign of the fire is a smoke, which comes through from beneath the surface. Peat fires can last for months, nondependent on wind, precipitation, and other weather changes. The danger of peat fires is also the creation of hollows (often with heat) inside the burnt peat during burning, where people, animals, and machines can be trapped.

Statistical data [1] reveal that fires in the peatlands of Ukraine, especially over the recent years, are actually the local environmental disaster of the region where they happen. The reason for such fires at the beginning of autumnal field works and the season of hunting is often the human factor. Specifically, hunters, fishermen and tourists who camp in ecosystems, as well as private household owners, agricultural workers who make a fire, blaze out dry grass in open territories, and stubble – in the fields. For example, the last large fire in the peatlands of Ukraine happened on September, 17, in Cherkasy region, near the village Irdyn. Dry grass caught fire and the sites of fire appeared in peat fields (Fig. 1). When the wind changed, the settlements Irdyn, Bilozirya and Dubiyivka witnessed a smoke in the air, which typically causes health problems for people who suffer

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from heart and nerve diseases, respiratory system problems. On September, 18, the state of emergency was declared by the decision of the board of special state commission. At the place of the incident, the mobile operative surveillance group found sites of burnt dry greenery covering the area of about 51 hectares.

Fig. 1. Fire in the peatland, the village of Irdyn, Cherkasy oblast

A permanently acting squad consisting of 4 subdivisions of The State Emergency Service of Ukraine department from the oblast center was deployed in the region of the village Irdyn, as well as fire brigades from the local forestry administration and cadets from the Cherkasy Institute of Fire Safety named after Chornobyl Heroes of National University of Civil Protection of Ukraine of Ukraine.

Employees of the forestry administration used tractors to perform fire diking and create reclamation bands around dangerous sites.

Statistics on fires in the peatlands over the last years have shown how bad urban dwellers, in particular, suffer from smoke caused by such fires. Thus, it is especially important to restrict peat fire propagation. Our work's objective is to search for materials that are capable of eliminating the propagation of peat fires in order to protect settlements that are adjacent to them.

2. Literature review and problem statement

The study of issues related to peat fires can be divided into two main directions. The first direction implies determining the consequences of fires for natural ecosystems. Specifically, paper [2] considers the danger of fire in the peatlands of Great Britain and the effects of environmental pollution. The authors established the volume of emissions of carbon oxides into the air and determined a share of emissions among all sources of atmosphere pollution. In article [3], peat fires are generally considered to be the main factor that affects the state of the ecological situation in the Indonesian region.

As paper [4] states, different toxic substances can be released during peat burning. Benzene is considered to be the most dangerous product of peat burning. Thus, for the peatlands located near settlements, it is important to work out measures for preventing fires in peatlands. Authors of studies [2–4] pay special attention to the environmental impacts of peat fires and the necessity to improve fire protection of peatlands, however, they do not propose any specific solutions that could improve the situation.

The second direction of research tackles the development of techniques for effective suppression and prevention of possible fires. Large moisture content in a peat layer is considered as the main factor [5], which restricts possible ignition and further propagation of burning. It was established that moisture content must exceed 200 % in order to stop smoldering peat burning.

In order to extinguish peat, paper [6] analyzed the use of sprayed jets of water. It was proven that the extinguishing of peat may take up to 6 l of water per 1 kg. To reduce water consumption and ensure effective extinguishing, it is proposed to use special substances [7]. The use of additives makes it possible to improve peat capability for sorption and wetting.

Thus, the results of papers [5–7] show the need to use water and water extinguishing solutions in large quantities for fighting and preventing fires. It is not always possible to ensure and maintain the supply of the required volume of water in arid regions.

To restrict the propagation of fire in a peat layer, it is promising to use the barriers made of bulk nonflammable material that has low thermal conductivity [8]. Such barriers are constructed by cutting narrow slits, filled with river sand, or with bentonite clay, which can be obtained from local quarries. When using such obstacles, it is necessary to predict the period of their effective work, depending on their thickness and material. At the same time, there is no procedure for defining the parameters of fire protection barriers in peatlands, meant to restrain propagation of fires and create conditions for their extinguishing.

Thus, there is a need to substantiate parameters of fire protection barriers in peatlands in order to prevent the propagation of burning. The proposed solutions should make it possible to build effective anti-fire barriers taking into consideration available mineralized materials and features of peat composition.

3. The aim and objectives of the study

The aim of present study is to identify the patterns of geometrical parameters of barriers to the propagation of fires in peatlands and their fire-retardant capacity to serve the scientific basis for creating a new method to restrain fires in peatlands.

To accomplish the aim, the following tasks have been set:

– to perform mathematical modeling of thermal processes in the system peat layer – fire barrier;

– to determine the time of reaching the dangerous temperature in a peat layer depending on the thickness of a barrier;

– to devise a procedure for designing fire protection barriers made of mineral materials.

4. Study of structural approaches to restricting the propagation of fires in peat layers

To solve the set tasks on the prediction of behavior of the system peat layer – barrier, it is required to devise a procedure for determining temperature distributions in layers of a peat layer and in the proposed barrier. A thermal problem

on heat propagation in the described system can be stated as follows.

1. A fire in a peatland extends from top to bottom with a certain constant speed.

2. Temperature in the region where peat is fully burned is constant, and it equals a mean constant value.

3. Thermal-physical properties of peat and the material of the barrier may depend on temperature.

4. Temperature in the region of peat burning is constant.

5. Heat transfer between the region of the underground fire and the material of the firefighting barrier has only a radiant component because its share is dominating.

6. A condition for the ignition and onset of fire propagation in a peat layer, which is protected by the fireproof barrier, is that the temperature of ignition in the respective estimated region has been exceeded.

Fig. 2 shows geometrical configuration of the estimated region.

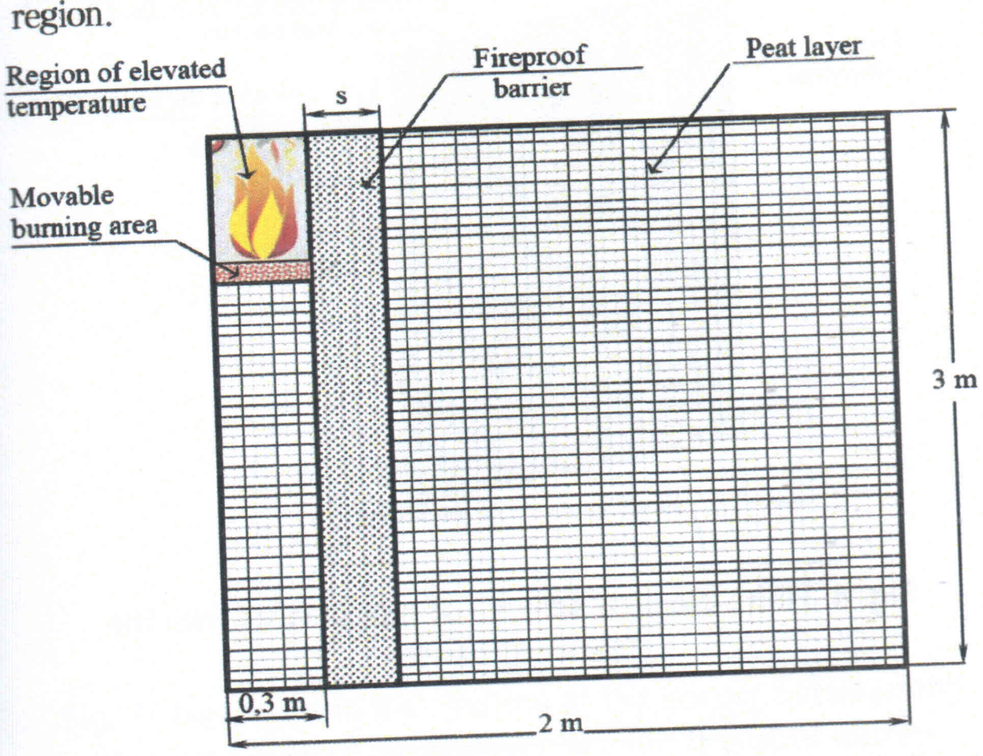

Fig. 2. Geometrical configuration of the estimated regions of the system peat layer-fireproof barrier

It is possible, when calculating, to apply the equation of nonstationary thermal conductivity with the boundary conditions of kind I and III. A thermal conductivity equation for the two-dimensional estimated region can be written in the following form [9–11]:

$$Cv(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right). \quad (1)$$

Fig. 3 shows schematic of accepted boundary conditions (BC).

Thermal effect on the estimated region from the zone of elevated temperature, which forms in the region where a peat layer had been burned and released the heat, can be described by the boundary conditions (BC) of kind III that are recorded in the following form:

$$-\lambda(T)\frac{\partial T}{\partial x}\Big|_{x=0,3\text{m}}=\alpha_B(T_P-T_W), \quad (2)$$

where α_B is the coefficient of radiant heat exchange, W/(m^2·°C); T_P, T_W are the temperatures of fire environment and the surface of a fireproof barrier, respectively, °C; x is the current spatial coordinate.

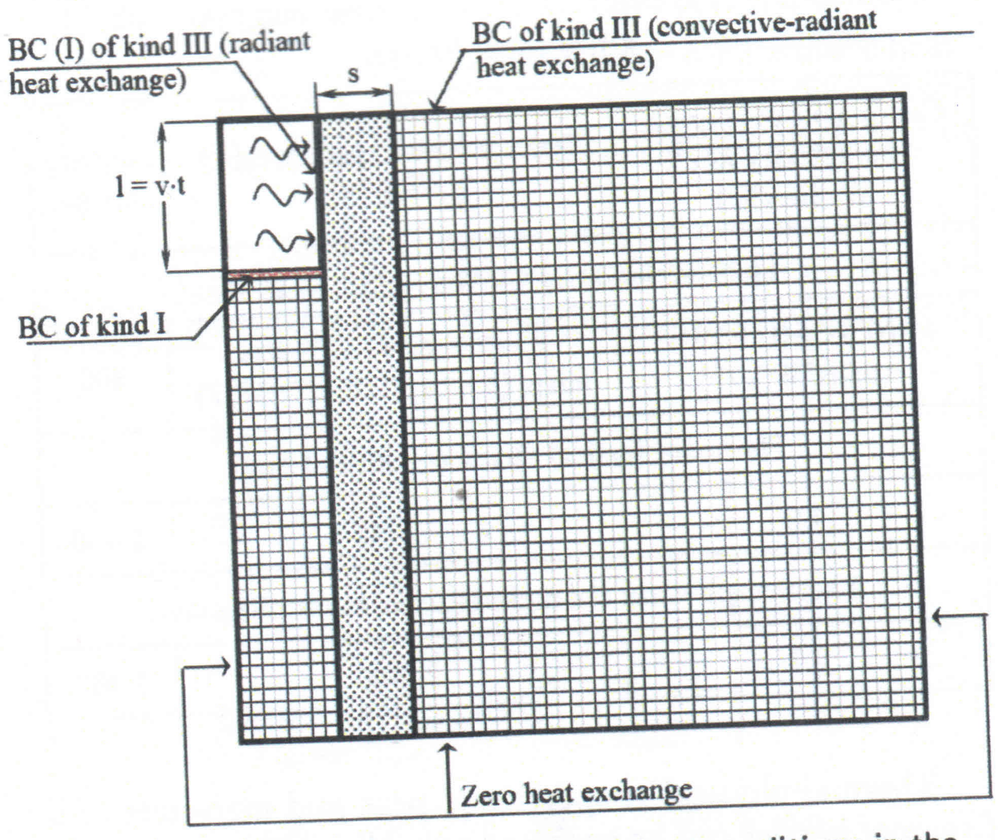

Fig. 3. Schematic of accepted boundary conditions in the estimated region

The heat exchange coefficient takes into consideration the effect of infrared radiation and is determined from formula [9–12]:

$$\alpha_B=\varepsilon\cdot\phi\cdot\sigma\cdot\frac{T_W^4-T_P^4}{T_W-T_P}, \quad (3)$$

where ε is the degree of blackness of the surface of a barrier; σ=5.67×10^{-8} W/(m^2·°C) is the Stefan-Boltzmann constant; φ=1 is the radiation form-factor.

Thermal effect in the estimated region from the side of a burning zone can be described by BC of kind I (Fig. 3). BC of kind I can be represented by expression:

$$T_W\big|_{y=L-l}=T_b, \quad (4)$$

where T_b is the temperature of peat burning; $l=v\times t$ is the height of the layer where peat had been entirely burned out.

A condition of heat transfer through the surface of a barrier and a peat layer, when burning is not propagated to the atmosphere, can be described by boundary condition of kind III in the following form:

$$-\lambda(T)\frac{\partial T}{\partial y}\Big|_{y=L}=\alpha_k(T_A-T_W), \quad (5)$$

where T_A is the temperature of the surrounding environment; α_k is the heat exchange coefficient that takes into consideration the effect of convection and infrared radiation.

Initial data that are employed in line with [13] for calculations are compiled in Table 1.

Table 1

Initial data for the calculation of temperature distribution in the system peat layer – fireproof barrier

Initial temperature of layer, °C	Temperature of surrounding air, °C	Temperature of peat burning, °C	Temperature of peat ignition, °C	Temperature in the center of peat fire, °C	Degree of blackness of the barrier surface	Degree of blackness of soil surface	Heat exchange coefficient between soil and air W/(m·°C)	Speed of propagation of the front of peat burning, mm/min
20	20	475	225	720	0.7	0.9	9	2

Thermal-physical characteristics of peat and materials of a fireproof barrier are given in Table 2.

Table 2

Thermal-physical characteristics of peat and materials of a fireproof barrier

Coefficient of thermal conductivity $\lambda(T)$, W/(m×°C)	Specific heat capacity, $c_p(T)$, J/(kg×°C)	Density, kg/m^3
Thermal-physical characteristics of peat		
$\lambda=(0.585-0.495W+0.987W^2)\ T^{0.2}$	$c_p=(765.0-1{,}577.8W)\times \exp[(0.64\ 10^{-3}+0.0175W)T]$	400
Thermal-physical characteristics of sand		
1.9	1,700	1,650
Thermal-physical characteristics of bentonite clay		
0.7	2,500	1,360

Thermal-physical properties of peat and materials of a fireproof barrier can be accepted according to recommendations [13–16].

5. Results of research of the model of a fireproof barrier

The equation of nonstationary thermal conductivity (1) for a given case has no analytical solutions and can be solved only numerically [9, 10, 17]. A method of finite elements was used to solve it [18, 19]. Its implementation is carried out in accordance with the developed estimation procedure. According to this procedure, estimation is performed using the following procedures.

1. A geometrical model is built, applying BC, accordingly, to Fig. 2, 3.

2. A cycle is organized, in the course of which a temperature front corresponding to BC (3) shifts down at the speed of propagation of the burning front.

3. To implement an appropriate change in the estimated region, a principle of the "death of finite elements" is applied, which implies excluding finite elements that correspond to the destroyed layer of peat as a result of burning from the estimated scheme.

4. The estimation is carried on as long as the temperature at any point of the protected plot of a peat layer does not reach the temperature of peat ignition.

5. The estimation is repeated for the barrier of a different thickness and made of a different material.

In order to implement such an algorithm, a finite-element scheme was created, shown in Fig. 4, and then we used the above-described mathematical apparatus. When implementing a computational process, we accepted parameters of the algorithm of numerical integration, given in Table 3.

It becomes clear as a result of the performed calculations that peat can entirely burn out in 28 hours, which is why, over the last temperature distribution, all the finite elements of the site of peat layer exposed to burning are excluded from the estimation scheme.

Fig. 5 shows temperature distribution at the border between the protected site of a peat layer and the fireproof barrier.

Table 3

Parameters of computational process

Parameter of computational process	Value, unit
Analysis type	Unsteady
Automatic selection of integration step	Included
Time step of integration	1,800 (30), s (min)
The smallest time step	30, s
The biggest time step	1,000, s
Maximal number of iterations	1,000
Technique for applying a load	Stepwise
Type of computational scheme	Implicit
Accuracy of the convergence of calculations	0.005 (0.5), (%)

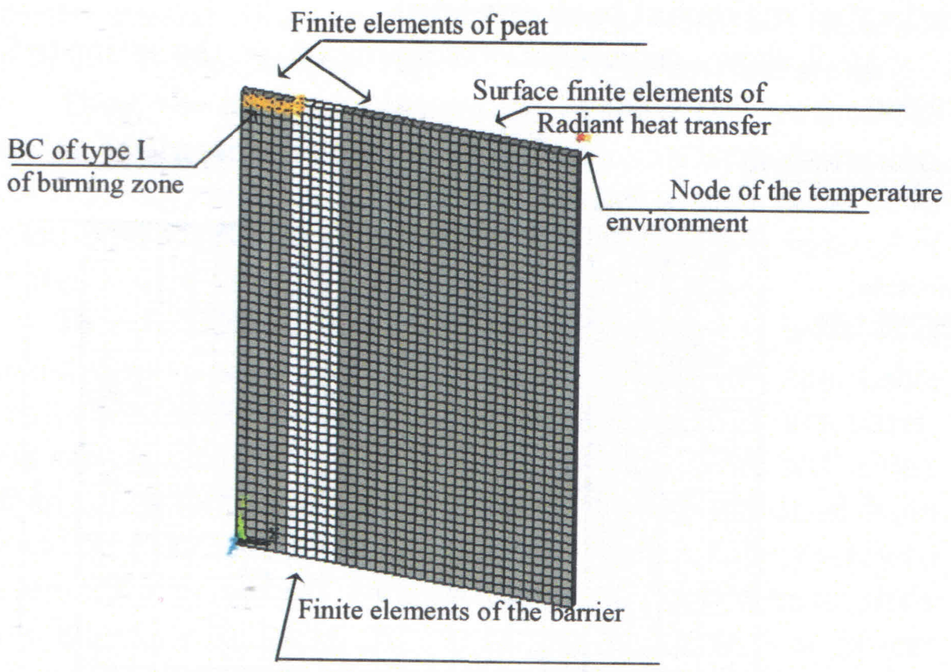

Fig. 4. Finite-element scheme of a peat layer with the fireproof barrier

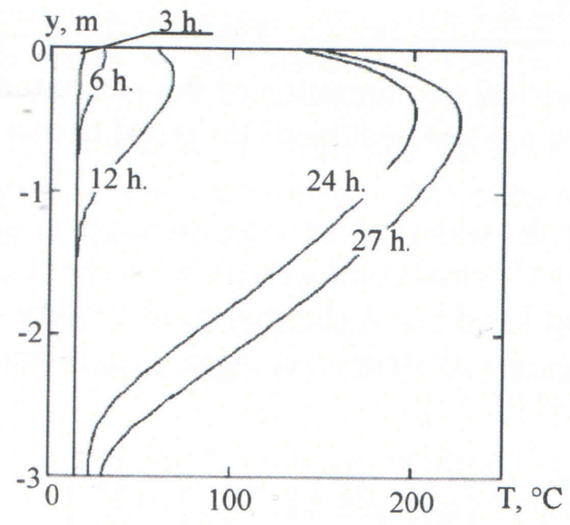

Fig. 5. Distribution of temperatures at the border between the protected site of a peat layer and the fireproof barrier made of river sand with a thickness of 300 mm at different points of time in the course of development of an underground fire

Fig. 6 shows dependences of temperature of the points at the border between the protected site of a peat layer and the fireproof barrier made of bentonite clay depending on the time of development of an underground fire.

Temperature distributions for a barrier made of bentonite clay also exhibit high efficiency of the proposed technical solutions related to the fireproof protection of peatlands from fire propagation.

Fig. 7 shows temperature distribution at the border between the protected area of a peat layer and the fireproof barrier made of bentonite clay.

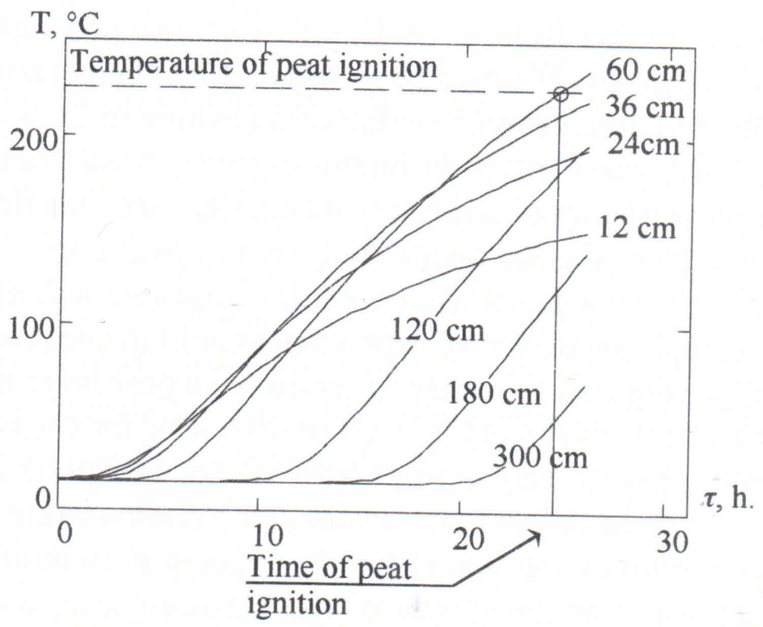

Fig. 6. Temperature dependences of certain points at the border between the protected site of a peat layer and the fireproof barrier made of river sand at different depths from its surface

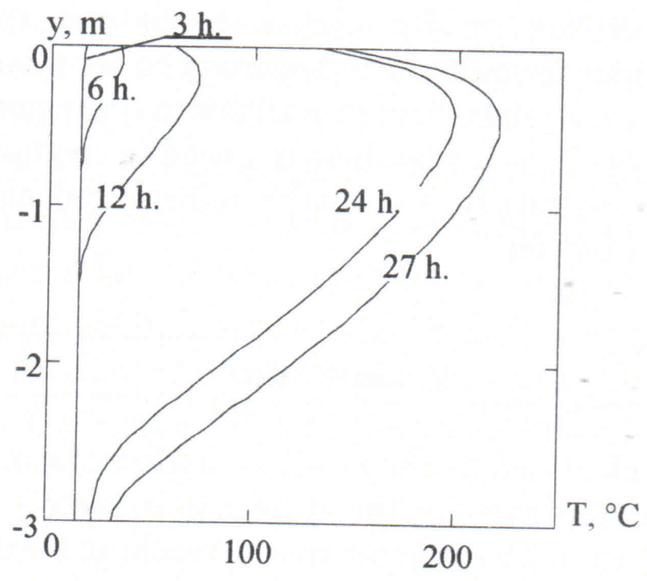

Fig. 7. Temperature distribution at the border between the protected area of a peat layer and the fireproof barrier made of bentonite clay with a thickness of 180 mm at different points of time in the course of development of an underground fire

Fig. 8 shows dependences of temperature of the points at the border between the protected section of a peat layer and the fireproof barrier made of bentonite clay depending on the time of development of an underground fire.

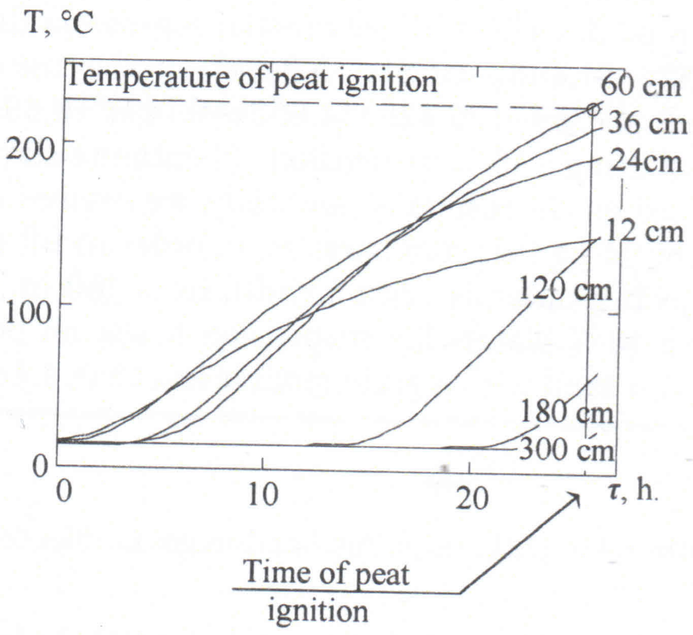

Fig. 8. Temperature dependences of some points at the border between the protected section of a peat layer and the fireproof barrier made of bentonite clay with a thickness of 180 mm at different depths from its surface

One can see that a given barrier is also an effective protection against the propagation of fire in peatland as the temperature in a protected area reaches the dangerous value in 25.4 hours under conditions of intensive burning of peat next to a barrier.

To undertake a more detailed study of temperature heating regimes of peat layers, we constructed time dependence charts of temperatures of the points in the protected area of a peat layer.

In order to identify patterns of dependence of time of the onset of dangerous temperature of peat ignition in the protected area, we constructed respective charts, shown in Fig. 9.

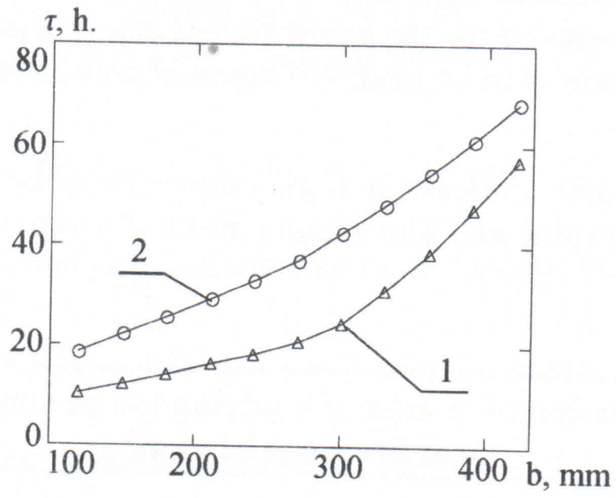

Fig. 9. Dependences of time of the onset of dangerous temperature for peat ignition on thickness of a barrier: 1 — made of river sand; 2 — made of bentonite clay

Charts in Fig. 9 indicate that the fireproof barrier made of bentonite clay is more effective. At lower thickness, it allows for longer protection. This is explained by the fact that due to a larger moisture content it has higher heat capacity; at the same time, it has lower density and smaller coefficient of thermal conductivity.

When designing fireproof barriers for peat layers, their thickness is an important parameter. That is why, in the case of automated selection with respect to time that is required to provide for the protection of a certain area of the peat layer, it is proposed to employ a regression analysis. The formula we obtained could be applied for solving the above problem.

To perform a regression analysis, it is proposed to use a polynomial of the third order; such a choice is predetermined by the shape of curves in the chart shown in Fig. 9. Parameters for the regression dependence were obtained using the Newton method. Table 4 gives the obtained parameters of regression functionals.

Table 4

Parameters of regression dependences of thickness of a barrier on time, which is required to provide for the protection of a peat layer

Regression coefficients $b=a_0+a_1\tau+a_2\tau^2+a_3\tau^3$	a_0	a_1	a_2	a_3, $\times 10^{-3}$	Error, %
Barrier made of river sand	−141.526	31.406	−0.681	5.319	0.5
Barrier made of bentonite clay	−106.429	14.653	−0.149	0.692	0.4

Fig. 10 shows charts of the obtained regression dependences.

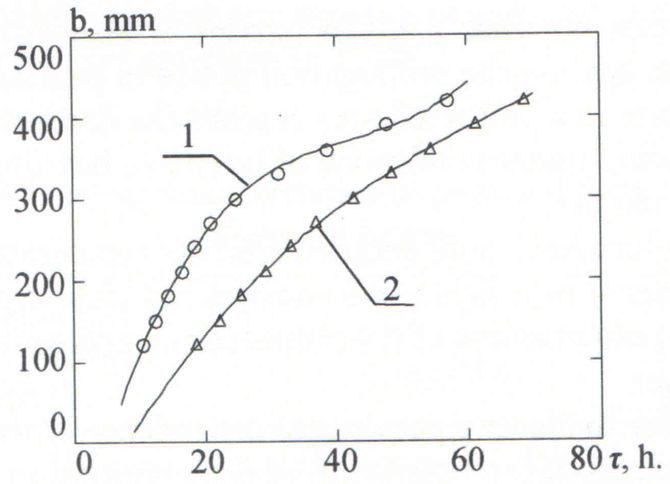

Fig. 10. Regression dependences of thickness of a barrier on the time, required for the protection of site of a peat layer: 1 — made of river sand; 2 — made of bentonite clay

The charts indicate a high convergence between the obtained results and the results derived from theoretical estimation.

6. Discussion of results of studying the parameters of peat fireproof barriers

The proposed fireproof barriers could be used as an alternative technique for restricting the propagation of fires in peatlands. The main advantage implies the minimization of amount of water required for further extinguishing by restricting the burning area. While preventing fires, such an approach requires a one-time expenditure in contrast to the technique that requires to permanently increase the moisture content in peat.

Thus, in order to design a protection barrier, we proposed a sequence of the necessary actions. Based on the operational situation in the area where peat layers are located, the sections that must be protected are defined. The areas that must be protected can be identified using modern geoinformation systems. It is necessary to take into consideration the location of potentially dangerous facilities in these territories and the availability of forces and means of fire-fighting units.

The time that would enable the fireproof protection of the defined area is calculated with respect to certain factors. Specifically, depth of peat layers, time for arrival of fire units and their tactic capabilities, time needed for the fire localization, evacuation of people and property, etc.

By applying data from Table 4, minimal thickness of the protection layer of a fireproof barrier is calculated, depending on the type of the material used.

Given the estimated thickness of a barrier, the appropriate working milling cutter is selected for a slit cutter in order to construct the designed fireproof barrier.

Temperature distributions, shown in Fig. 5, 8, indicate high efficiency of the proposed technical solutions related to the fireproof protection of peatlands from fire propagation. The calculations performed have shown that temperature in the protected area grows to a dangerous value in 24.5 hours under conditions of intensive burning of peat close to a barrier. Therefore, the proposed fireproof barriers are the effective protection from the propagation of fire in peatland.

The regression dependences obtained have some limits for practical application. These dependences hold in the intervals of the time required to protect a section of a peat layer for the barrier made of river sand, from 3 to 60 hours; for the barrier made of bentonite clay – from 5 to 70 hours. For the time values that are smaller than the smallest extreme value of the respective intervals, it is technically impossible to build such barriers as there are no standard equipment for such tasks. As regards the values that are larger than the highest extreme values for respective intervals, the construction of such barriers is impractical because rescue squads would necessarily arrive within such a time period and localize the fire.

Research results could be applied when designing fireproof barriers for actual peatlands. At the same time, from the economic viewpoint, it is necessary to consider a possibility to use materials that are available in the region of peatland location. That is why there is a need to conduct further study to investigate the use of other mineralized materials as a filler for a barrier.

7. Conclusions

1. We identified as the result of mathematical modeling of thermal processes in the system peat layer – fireproof protection the patterns in the time of reaching the dangerous temperature in a peat layer that was protected. It was established that the time of reaching the dangerous temperature in a peat layer for the barriers made of river sand and bentonite clay is not less than 1 day from the onset of action of the burning temperature.

2. In order to find the time of reaching the dangerous temperature in a peat layer depending on the thickness of a barrier, we constructed regression dependences. By using mathematical modeling of the processes of fire development, we established a parabolic dependence of thickness of a fireproof barrier b, mm, on time τ, hours, which is required to provide protection of an object. The dependence can be described by polynomial regression functions $b=-141.526+31.406\tau-0.681\tau^2+5.319\tau^3$ – in the case of using river sand, and $b=-106.429+14.653\tau-0.149\tau^2+0.692\tau^3$ – in the case of using a 10-% suspension of bentonite clay.

3. Based on the results of our study, we devised a procedure for building fireproof barriers, in order to fill the fireproof gaps in peatlands, with a width from 180 to 300 mm made of a 10-% water-clay suspension based on bentonite clay, or river sand with a grain module less than 1.48.

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DEVELOPMENT OF THE TECHNIQUE FOR RESTRICTING THE PROPAGATION OF FIRE IN NATURAL PEAT ECOSYSTEMS (p. 31-37)

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In order to reduce the scale of peat fires, we suggest using fire barriers made of mineralized materials. The incombustible materials are proposed, specifically sand and bentonite clay, to be used for filling up artificial slits cut in a peat layer. Construction of anti-fire barriers requires a one-time expenditure, in contrast to the existing techniques for fire prevention that require continuous pumping of water in order to increase moisture content in peat.

Mathematical modeling of thermal processes in the system peat layer–fire barrier was performed. The time of reaching the dangerous temperature by the protected layer, for the barriers made of river sand with a thickness of 300 mm, and for those made of bentonite clay with a thickness of 180 mm, is not less than 1 day. Given this, we have proven the effectiveness of the proposed barriers.

By using mathematical modeling of the processes of fire development, a parabolic dependence was built of the thickness of fire protection barrier b, mm, on time τ, hours, required to protect an object. We established parameters for regression dependences of thickness of a barrier on the time required to protect a peat layer.

The result of present research is the proposed technique for designing fire protection barriers made of river sand and bentonite clay, based on the obtained patterns and regression dependences.

Research results could be used in the process of designing fire protection barriers for actual peatlands.

Keywords: temperature of peat layer, mineral fire barrier, fire safety of peat.

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