Досліджено використання подвійного горючого заряду для створення протипожежного бар'єру за рахунок вибуху. Встановлено, що ширина протипожежного бар'єру залежатиме від кількості зарядів та енергії вибуху, яка визначається діаметром заряду. За результатами дослідження отримана залежність ширини протипожежного бар'єру від параметрів подвійних зарядів. Обгрунтовано застосування подвійного горючого заряду в залежності від типу рослинності

Ключові слова: локалізація природних пожеж, протипожежний бар'єр, вибуховий спосіб, горючий заряд

Исследовано применение двойного горючего заряда для создания противопожарного барьера за счет взрыва. Установлено, что ширина противопожарного барьера будет зависеть от количества зарядов и энергии взрыва, которая определяется диаметром заряда. По результатам исследования получена зависимость ширины противопожарного барьера от параметров зарядов. Обосновано применение двойного горючего заряда в зависимости от типа растительности

Ключевые слова: локализация природных пожаров, противопожарный барьер, взрывной способ, горючий заряд

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NUMERICAL SIMULATION OF THE CREATION OF A FIRE FIGHTING BARRIER USING AN EXPLOSION OF A COMBUSTIBLE CHARGE

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1. Introduction

Up to 400 thousand natural fires happen every year on the planet. They cause significant losses. Flora and fauna representatives die, soil fertility diminishes, the environment deteriorates, all because of natural fires. In addition, fires lead to an increase in the amount of carbon dioxide in the atmosphere, which causes global warming on Earth [1].

People widely use methods of termination of a spread of combustion by creation of protective fire barriers for localization of natural fires. Physical-mechanical [2–4] or explosive [5–7] methods provide establishment of fire barriers at present. The physical-mechanical method is used for the creation of a stripe with a help of engineering techniques and manual means, and the explosive method – with a help of cord or pressure charges. The advantage of the explosive method for the establishment of a fire barrier is a possibility of its application in hard-to-reach areas. In this case, the explosive method can increase the productivity of the establishment of fire barriers.

There are restrictions for wide application of the explosive method of the establishment of fire barriers with cord or pressure charges, due to a need for complex dangerously explosive work on delivery, stowage and explosion of charges. Explosive operations in a limited time lead to an increase in the risk factor. A long time of conduction of explosive work and insufficient width of a fire barrier created by a cord charge are reasons for low productivity of the method. Specifically, a cord charge of the ESH-1P type provides the establishment of a fire barrier of 1.4 m width, and, as a rule, a fire barrier of 3 to 15 m width is required for localization of natural fires.

It is expedient to use combustion charges filled with a fuel-air mixture as an alternative to cord charges. A fuel-air mixture consists of combustible gas and air. A combustion charge is a polyethylene membrane filled with fuel and air mixture. It has a number of benefits:

1) increased security during work with charges;

2) an increased pulse of pressure, which occurs for the same explosive energy comparing with a condensed charge;

3) high specific heat of combustion of fuel.

Therefore, the development of a technology of explosion of a combustion charge for the establishment of a fire barrier is aimed at improvement of the explosive method of localization of natural fires by increasing productivity and increasing the width of a fire barrier.

A use of mathematical apparatus and modern computer technology can reduce material costs for investigation of various complex processes. Therefore, there are developed mathematical models that investigate the impact of an explosion on vegetation [7, 8]. Let us consider the possibility of application of known models to investigate an explosion of a combustion charge for the establishment of a fire barrier.

A need for further development of the technology of explosion of a combustion gas charge for the establishment of a fire barrier substantiates the expedience of the study.

2. Literature review and problem statement

There are many studies at present, which consider methods of localization of natural fires by the establishment of fire barriers by an explosive method. Thus, paper [8] proposes the use of a cylindrical reflector. There is a container with a powder in the middle of a reflector. It creates a screen to stop fire during an explosion. Authors of paper [9] use a reflector with explosive substance buried in the ground before an explosion to create a fire barrier. An explosion caused by explosive substance clears the ground's surface. The use of reflectors reduces productivity of the explosive method.

Authors of article [10] use a shell to establish a fire barrier. A shell has two tanks: one with explosive substance, the other – with water. An explosion of a charge with explosive substance produces water fog, which prevents a further spread of fire. The disadvantage of the method is large mass of charge and water tanks. In paper [11], authors place a pressure hose charge in front of fire and blow it up. The disadvantage of the method is the use of dangerous explosive substances and transition of ground fire to crown fire due to tree damages caused by explosion.

Article [12] proposes using a container with extinguishing powder. An explosion of a charge provides dispersion of extinguishing agent and its release as fog to a burning surface. The disadvantage of the method is delivery of a charge into the center of fire, as well as destruction of extinguishing agent during an explosion. And in paper [13], authors deliver a combustible mixture of non-flammable (inert) gas with a flammable gas (propane or butane) to the fire center. Authors do not explain how to obtain the mixture and how to deliver it to the center of fire.

An air shock wave generated by an electrical explosion of conductors clears a stripe in a forest [14]. One should apply extinguishing agent to the created fire barrier after an explosion. The disadvantage of the method is the complexity of its implementation due to a high cost of work required and a constant source of electric current.

Article [15] presents theoretical and experimental studies of the establishment of fire barriers by wire cord charges in more detail.

Authors of a paper [15] developed a mathematical model of the interaction of shock waves with vegetation and a front of natural fires in relation to condensed explosive substances. The interaction of a shock wave with phytocoenosis and a front of natural fire was simulated in one-dimensional and two-dimensional formulation of tasks. The mathematical model [15] takes into account that, while propagating through the vegetation, a shock wave and an accompanying stream cause a partial breaking of vegetative combustible material with the involvement of the mass to the motion. That is, resistance of the environment affects a course of a gas flow in the aggregate. Obviously, a spatial structure of a shock wave front will be different at a microlevel in each case. But on a large scale, a shape of a shock wave source determines a shock wave front. Authors of paper [15] introduced a parameter, which characterizes resistance of a vegetation volume unit, into the mathematical model. It ranged from 0 (open space) to 0.7 (thick, young coniferous forest) during the research. The research in paper [15] showed that the critical value of density of a layer of vegetative combustible material in young coniferous forest is $\rho_{*}=0.2\ \mathrm{kg/m^3}$. Such critical values of density are achieved at the degree of breaking of vegetation elements equal to 0.75. According to article [15], such a degree of breaking is realized at an excess pressure of about 1.2 atm.

The results of the studies do not give possibility to analyze the efficiency of combustion charges for the establishment of fire barriers in connection with a significant difference in parameters of an explosion of combustion charges and cord charges. Therefore, the mathematical model [15] does not make possible to investigate a process of the establishment of a fire barrier produced by an explosion of a combustion charge. Experimental results [15] relate only to cord charges. These results do not give possibility to evaluate the energy efficiency of combustion charges.

Studies [16, 17] present a mathematical model, results of numerical and experimental studies on an explosion of a combustion charge for the establishment of a fire barrier. Authors of papers [16, 17] carried out a study on the impact of an explosion of combustion charges on forest vegetation and grass cover. They obtained empirical dependences of specific distribution of vegetation mass on the ground's surface after an explosion in dependence on the diameter of a charge.

The coincidence of results of numerical and experimental studies [16, 17] proves that the given model is adequate. It also confirmed the effectiveness of the establishment of a fire barrier produced by an explosion of a combustion charge. But the question of determination of optimal charge parameters, which provide the establishment of an energy efficient barrier, remains not fully disclosed.

3. The aim and objectives of the study

The aim of present study is to determine an optimal diameter of a combustion charge, which provides the establishment of a fire barrier energy-efficiently, based on results of numerical studies.

The following tasks were solved to achieve the objective:

– conducting numerical studies on the dependence of a width of a fire barrier on a diameter of a double combustion charge;

– substantiation of an optimal width of a fire barrier for localization of natural fires based on the results of numerical studies.

4. Mathematical model of the establishment of a fire barrier produced by an explosion of a combustion charge

There is a description of a mathematical model in a work [16]. The mathematical model of the impact of an explosion of combustible charges is represented by a system of equations, which describes the non-stationary three-dimensional flow of a two-component gas mixture in the Cartesian coordinate system [18, 19]:

$$\frac{\partial\rho}{\partial t}+\frac{\partial\rho u}{\partial x}+\frac{\partial\rho v}{\partial y}+\frac{\partial\rho w}{\partial z}=0, \quad (1)$$

$$\frac{\partial\rho u}{\partial t}+\frac{\partial\left(P+\rho u^2\right)}{\partial x}+\frac{\partial\rho uv}{\partial y}+\frac{\partial\rho uw}{\partial z}=f_x, \quad (2)$$

$$\frac{\partial\rho v}{\partial t}+\frac{\partial\rho uv}{\partial x}+\frac{\partial\left(P+\rho v^2\right)}{\partial y}+\frac{\partial\rho vw}{\partial z}=f_y, \quad (3)$$

$$\frac{\partial\rho w}{\partial t}+\frac{\partial\rho uw}{\partial x}+\frac{\partial\rho vw}{\partial y}+\frac{\partial\left(P+\rho w^2\right)}{\partial z}=f_z, \quad (4)$$

$$\frac{\partial E}{\partial t}+\frac{\partial\left[(E+P)u\right]}{\partial x}+\frac{\partial\left[(E+P)v\right]}{\partial y}+\frac{\partial\left[(E+P)w\right]}{\partial z}=0, \quad (5)$$

where

$$f_x=-sc_d\cdot\rho u\sqrt{u^2+w^2+v^2};$$

$$f_z=-sc_d\cdot\rho w\sqrt{u^2+w^2+v^2};$$

$$f_y=-sc_d\cdot\rho v\sqrt{u^2+w^2+v^2}$$

is the projection of resistance force onto the coordinate axis (sc_d is the parameter, which characterizes strength of resistance of a volume unit of phytocoenosis); ρ, T, P are the density, temperature and pressure of a gas phase, respectively; e is the internal energy of a mass unit of a gas phase; t is the time; u, v, w are the components of a velocity vector of a gas flow; x, y, z are the coordinates in the Cartesian coordinate system; E is the total energy of a volume unit of a gas mixture:

$$E=\rho\left(e+\frac{1}{2}\left(u^2+v^2+w^2\right)\right).$$

We supplement the system of equations (1)–(5) by the law of transfer of components of a mixture, by the equations that determine thermophysical properties of components of a mixture [20, 21].

The width of a fire barrier will depend on the energy of an explosion, which, in particular, is determined by the diameter of a combustion charge. A spatial location of a charge in the phytocoenus and a number of charges applied and their relative position also affect the width of a fire barrier. Therefore, the problem was solved for different charges and conditions of location.

A base is the assumption that distribution of charges can increase the width of a fire barrier. Therefore, location of charges in the simulation field was set according to the scheme (Fig. 1) [16]. The distance taken between the charge axes is 2 m, which corresponds to the average distance between tracks of a fire vehicle. At high altitude of the ground combustible material, stowage of charges on a track makes possible to approach the ground and thus to increase the energy efficiency of an explosion.

The accepted gas state parameters correspond to the state of the environment at the initial moment in all the cells of the calculated area outside of a combustion charge. The velocity of an incident wind flow was set equal to q_z=3m/s as an average wind speed (in summer over a hot period) for the city of Kharkiv and the Kharkiv region [22, 23]. We investigated initial conditions for double combustion charges with a diameter d={0.95; 1.3}. We assumed that the thickness of a layer of ground combustible material is equal to h=0.1 m.

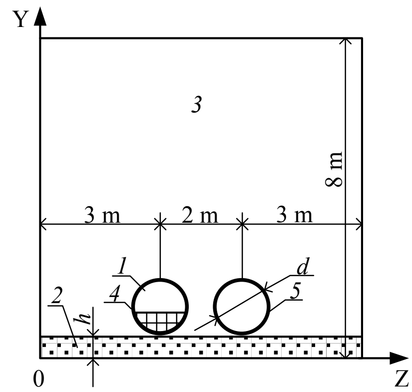

Fig. 1. Location of a combustible charge in the calculated area: 1 — detonation products, 2 — layer of vegetation, 3 — air, 4 — place of calculation, 5 — initial limit of the location of detonation products, h — thickness of a cover layer, d — initial diameter of a charge

Thus, initial conditions are as follows. In the area of detonation of a charge:

$$\left(y-h-\frac{d}{2}\right)^2+\left(z-\frac{H_z}{2}+1\right)^2<\frac{d^2}{4},$$

$$\left(y-h-\frac{d}{2}\right)^2+\left(z-\frac{H_z}{2}-1\right)^2<\frac{d^2}{4},$$

$$0<x<H_x, \quad (6)$$

we accepted: $P|_{t=0}$=1.4 MPa; $T|_{t=0}$=3480 K; $\gamma|_{t=0}$=1,267, $u|_{t=0}$=0; $v|_{t=0}$=0; $w|_{t=0}$=0; $N|_{t=0}$=1.

In the airspace:

$$h<y<H_y,\ \ 0<x<H_x,\ \ 0<z<H_z,$$

$$\left(y-h-\frac{d}{2}\right)^2+\left(z-\frac{H_z}{2}+1\right)^2\geq\frac{d^2}{4},$$

$$\left(y-h-\frac{d}{2}\right)^2+\left(z-\frac{H_z}{2}-1\right)^2\geq\frac{d^2}{4}, \quad (7)$$

we accepted: $P|_{t=0}$=0.1 MPa; $T|_{t=0}$=293 K; $\gamma|_{t=0}$=1,4; $u|_{t=0}$=0; $v|_{t=0}$=0; $w|_{t=0}$=3 m/s; $N|_{t=0}$=0.

In the area of phytocenosis:

$$0<y<h,\ \ 0<x<H_x,\ \ 0<z<H_z, \quad (8)$$

we accepted: $P|_{t=0}$=0.1 MPa; $T|_{t=0}$=293 K; $\gamma|_{t=0}$=1,4; $u|_{t=0}$=0; $v|_{t=0}$=0; $w|_{t=0}$=0 m/s; $N|_{t=0}$=0.

Boundary conditions. A plurality of impenetrable sites, which collectively simulate the calculated area of surfaces represented the ground's surface. A non-flow condition existed on the surfaces mentioned: $q\vec{n}=0$, where $\vec{n}$ is the normal vector for this exact surface.

We used methods for solution of gas dynamics equations for shock waves, which propagate in the environment with resistance to a gas flow, to study processes that occur during an explosion of combustion charges.

5. Results of a numerical study on the establishment of a fire barrier produced by an explosion of combustion charges

Fig. 2, 3 show results of the calculation of the dynamics of pressure changes at the expansion of products of explosion of double combustion charges with an initial diameter of 0.95 m. We estimated that the beginning of collision of shock waves occurs in 1.5 microseconds under the above-mentioned conditions of charges location.

Collision of shock waves occurs in 1.2 ms for a diameter of a double charge of 1.3 m. As a result of reflection of shock waves there is an increase in pressure between charges, which provides a reliable breakdown of vegetative combustible material, for a diameter of a double charge of 1.3 m.

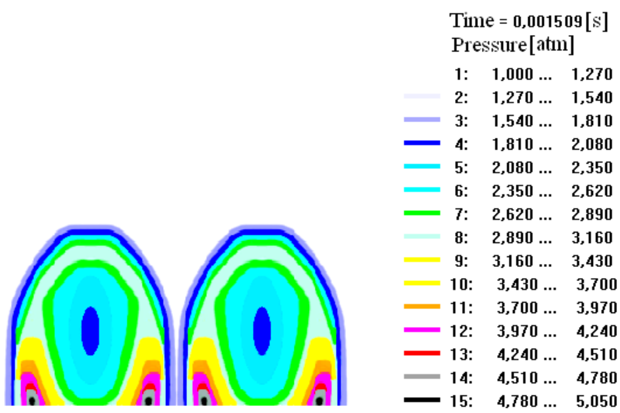

Fig. 2. Pressure field in the cross section of double combustion charges with a diameter of 0.95 m at a time of 1.5 ms from the start of the explosion

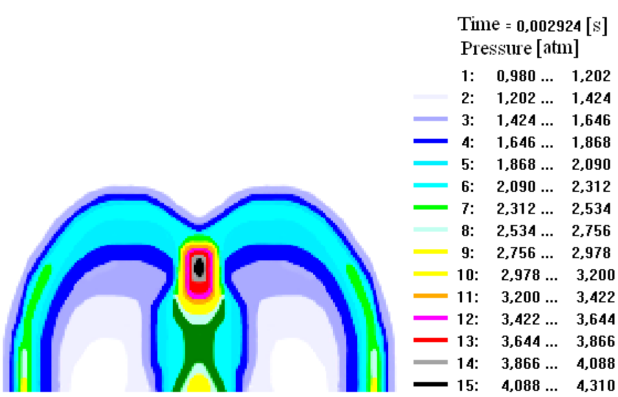

Fig. 3. Pressure field in the cross section of double combustion charges with a diameter of 0.95 m at a time of about 3 ms from the start of the explosion

There is also an increase in pressure on the ground's surface, along which propagation of a semi-cylindrical shock wave occurs, which increases the efficiency of clearing the ground's surface from ground-based combustible material.

A pressure drop to atmospheric pressure occurs in the area of charge location at the expansion of explosive products in 3 ms. After reflection of interacting shock waves, they propagate in the opposite direction (Fig. 4).

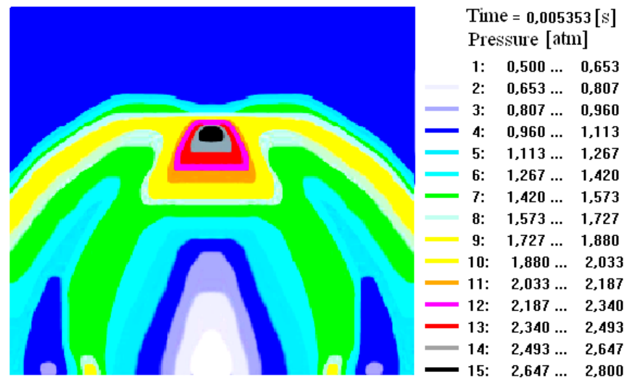

Fig. 4. Pressure field in the cross section of double combustion charges with a diameter of 0.95 m at a time of 5 ms from the start of the explosion

The dynamics of propagation of a shock wave in the atmosphere becomes hemispherical after some time even at diameters of combustion charges of 0.95 m. This ensures that rusty vegetative flammable material is removed beyond the stripe boundary (barrier) created by the explosion of a combustion charge.

Due to the explosion of double combustion charges with a diameter of 0.95 m, a fire barrier with a width of 4.5÷5 m can be created (Fig. 5).

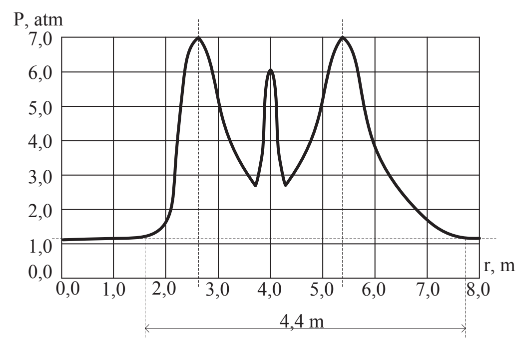

Fig. 5. Maximum values of pressure in a simulated layer of GSM with charge diameters of 0.95 m and a coefficient of resistance of the environment – 0.7

According to the calculations, it is evident that the use of double charges with a diameter of 1.3 m provides the establishment of fire barriers of about 8 m width (Fig. 6, 7).

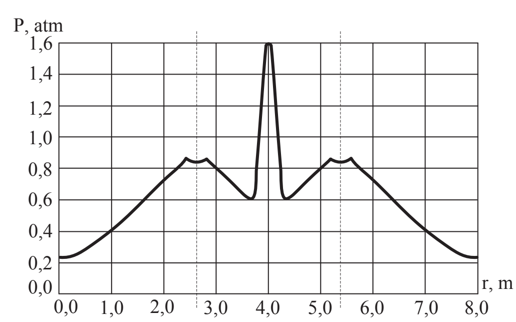

Fig. 6. Maximum values of pressure in a simulated layer of GSM with charge diameters of 1.3 m and a coefficient of resistance of the environment – 0.5

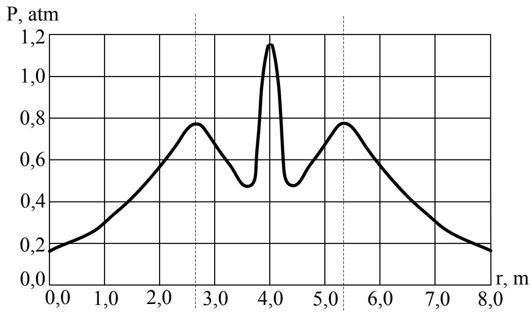

Fig. 7. Maximum values of pressure in a simulated layer of GSM with charge diameters of 1.3 m and a coefficient of resistance of the environment – 0.7

It is necessary to take into account that a decrease in the width of a fire barrier occurs when the mixture with a concentration approaches to the detonation limit. Therefore, an increase in specific energy of a combustion charge is expedient in this case.

We calculated the fields of pressure arising from an explosion of combustion charges in phytocoenus during a numerical study. The width of a fire barrier was determined based on the analysis of maximum values of pressure reached at the front of a shock wave. We obtained results of the establishment of a fire barrier produced by the explosion of double charges based on the results of numerical simulation above. They are given in Table 1.

Table 1

Width of a fire barrier at the explosion of double combustion charges

Charge parameters (number×diameter)	Width of a fire barrier, m at environment resistance coefficients sc_d		
	0.5	0.6	0.7
2×0.95	4.8	4.6	4.4
2×1.3	>8	8	7.5

According to the results of numerical studies, we found that when using a double combustion charge of 0.95 m diameter, the width of a fire barrier will be 4.4 m for coniferous forest, 4.6 m for mixed forest and 4.6 m for deciduous forest. If to establish a fire barrier by a double combustion charge of 1.3 m diameter, the width of a fire barrier will be 7.5 m for coniferous forest, 8 m for mixed forest and more than 8 m for deciduous forest.

6. Discussion of results of the study on the establishment of a fire barrier.

Combustion of vegetative combustible material accompanies fires in a forest. They have a spatial structure and characteristic vertical layers.

Leafy litter, moss, lichens, herbs, shrubs, young and adult trees form vegetative combustible material [24]. In the case of fire in a forest, burning of all vegetation, which comes on a way of fire, begins. An effective method of combating natural fires is the establishment of fire barriers, which prevents a spread and development of natural fires [25].

The analysis of regulations on fire safety [26] indicates the need to increase a width of fire barriers that are created by explosive methods.

In particular, in a paper [15], it is noted that a cord charge of the ESH–1P type provides the establishment of a fire barrier of 1.4 m width. If to consider a height of bushes and young trees in a forest, we can confidently say that the barrier of 1.4 m width is not able to stop natural fire. The width of the barrier should be at least 6 m due to overthrow of bushes and young trees.

A regulatory document [26] defines the following requirements for fire barriers, namely:

– fire ditch – a barrier for protection of forest areas from underground fires of 1.5–2.8 m width;

– fire barrier – a combined barrier, which consists of fire bridges and protective stripes of forest, which have been cleansed of vegetative combustible materials, to a height of up to 2 m.

According to the results of numerical simulation we have to apply a double charge of 1.3 m diameter to achieve the width of a fire barrier over 8 m under different conditions of application.

Comparing the results of the study with normative indicators and indicators of other authors [15, 24, 26], we can say that we can create a fire barrier of larger than 8 m width due to the use of explosion of combustion charges. The established fire barrier of 8 m width will protect vegetation from further spread of ground natural fire. Therefore, it is recommended to use double combustion charges of 1.3 m diameter for the establishment of fire barriers in vegetation massifs with a medium intensity of natural fire. The disadvantage is a lack of recommendations on the use of combustion charges to establish fire barriers, because of a lack of experimental research at present time. The conducted numerical study makes possible to confirm energy efficiency of application of combustion charges for the establishment of fire barriers.

The use of double combustion charges will reduce the cost and increase productivity of the establishment of fire barriers. In contrast to the ESH-1P charge, which consists of an explosive substance, a combustion charge consists of a shell filled with a mixture of gas (propane) and air. It can be noted that the cost of explosive substance will be significantly higher than the cost of combustible gas (propane).

Taking into account location of trees in the middle of a forest and the state of a ground, the use of engineering technology becomes inappropriate, and the use of cord charges can lead to trees falling. The use of combustion charges makes possible to establish fire barriers on rocky ground and among trees easily without damaging them. The use of combustion charge to establish a fire barrier can be applied in the technology of extinguishing grass forest and steppe fires.

Numerous studies on the establishment of a fire barrier produced by the explosion of a combustion charge are a continuation of earlier studies [16, 17], and we plan a series of experimental studies in the future.

7. Conclusions

1. We carried out numerous studies on the dependence of the width of a fire barrier on the diameter of a double combustion charge. We established that the width of a fire barrier depends on resistance of the environment (type of vegetation) and the diameter of a double combustion charge. We determined that the establishment of fire barriers is carried out due to the explosion of combustion charges by clear-

ing the ground combustible material, and excess pressure of an explosion should be at least 1.2 atmospheres.

2. We established the optimal width of a fire barrier for localization of natural fires according to the results of the numerical study. Thus, in order to establish a fire barrier of 4.8 m width, it is necessary to use a double combustion charge of 0,95 m diameter. To create a fire barrier of 8 m width, it is necessary to use a double combustion charge of 1,3 m diameter.

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