Improving the efficiency of extinguishing forest grass-roots fires with knapsack forest fire extinguishers

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Abstract. The most effective means of fighting forest fires is the timely detection of fires, monitoring and patrolling of recreation areas, extinguishing of unquenched fires. The purpose of the research is to increase the efficiency of extinguishing forest grass-roots fires with knapsack forest fire extinguishers based on constructive and technical solutions that ensure economical use of fire extinguishing agents. The article presents studies of the characteristics of sprayed water, water vapor, affecting the effectiveness of extinguishing. Optimal ratios of the design parameters of the developed knapsack forest fire extinguishers are given. With a short-term exposure to steam on the hearth, diffusion combustion stops. The condition for stopping the burning of wood is the cessation of flame combustion and cooling of coals formed during combustion to a temperature below the pyrolysis temperature, i.e. below 200 ° C. In the case of heterogeneous combustion, the effect of a jet of water vapor on the centers of smoldering is ineffective. To cool the diffusion flame torch, a steam consumption of 1.9 kg per kilogram of wood is required. The water vapor consumption required to dilute the gaseous pyrolysis products formed from one kilogram of wood is about 7 kg. The presented experimental studies confirm the effectiveness of sprayed water and steam as independent extinguishing agents and means of creating support strips. To achieve a critical level of moisture content, the thickness of the condensate film should be at least 0.1 mm. The effective velocity of the steam source is about 1.5-2.5 km/h.

1 Introduction

From 10 to 35 thousand fires in forests covering an area of up to 2.5 million hectares are registered annually in Russia. The main reason for their occurrence is related to the economic activity of people. It is known that most forest fires occur at a distance of up to 5 km from settlements, often in places where people rest [1, 2]. The most effective means of fighting forest fires is the timely detection of fires, monitoring and patrolling of recreation areas, extinguishing of unquenched fires.

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The most widely used for extinguishing forest fires is water and its solutions. To increase the extinguishing efficiency, additives that increase the wetting ability are also introduced into the water.

The most common technical means of extinguishing forest fires are portable knapsack forest fire extinguishers, not expensive, simple and reliable in design, filled with water and aqueous solutions with additives that increase fire extinguishing characteristics. A common disadvantage of which is low efficiency and high consumption of fire extinguishing agents.

Many Russian scientists have been engaged in research on the processes of extinguishing forest fires. Tactics and technology of extinguishing forest fires are considered in the works of S.V. Komissarov [1], Loshilov [2], D. A. Maslennikov, L. Yu. Kataev [3], S. V. Gundar [4].

A. S. Podolskaya [5], S. A. Loshilov [6], N. A. Romanova [7-8], A.V. Kolyada [9], V. S. Komarovsky [10], Yu. D. Motorygin [11] and others were engaged in forecasting the occurrence, spread and extinguishing of forest fires.

The works of S. V. Molokova [12], L.A. Zhuravleva [13-15] are devoted to the development of resource-saving environmentally safe technologies for extinguishing forest fires, in particular by steam.

With a significant variety of methods of extinguishing forest fires and their research, there is insufficient information about the use of small manual technical means, there is no generalized principle of calculation and justification of their choice, technology of use.

The scientific problem is to ensure the extinguishing of forest fires with minimal (economical) expenditure of extinguishing agents.

The purpose of the research is to increase the efficiency of extinguishing forest grass–roots fires with knapsack forest fire extinguishers based on constructive and technical solutions that ensure economical use of fire extinguishing agents.

To achieve the intended goal, the following tasks were set:

1. Conduct theoretical studies of the extinguishing properties of water vapor and sprayed water.
2. To develop devices and design and technical solutions for the creation of water vapor and sprayed water, to determine their design and technological parameters.
3. To experimentally investigate the efficiency of using water vapor and sprayed water when extinguishing various combustion foci combustion.

2 Materials and methods

An increase in the extinguishing efficiency is achieved by introducing surfactants into the extinguishing liquid. The intensity of lowering the surface tension of the liquid depends on the chemical composition of the wetting agent and its concentration.

Wetting is quantitatively characterized by the value of the wetting edge angle formed by a solid surface and tangent to the surface of the liquid at its point of contact with a solid. The smaller the edge angle, the better the wetting (Fig.1).

Upon contact with the surface of a solid, liquid droplets initially have a spherical shape (Fig. 1 a). Then the droplet spreads to the height h (Fig. 1 b), and the minimum thickness Δ (Fig. 1 c).

The forces acting on a drop can be divided into external forces (gravity and the force of interaction of liquid particles with solid particles) and internal (surface tension forces). The shape that a drop of liquid takes is determined by the ratio of these forces.

In the case under consideration (Fig. 1 d), due to the insignificant mass of the drop and the low gravity acting on it, we take the shape of a drop close to a ball.

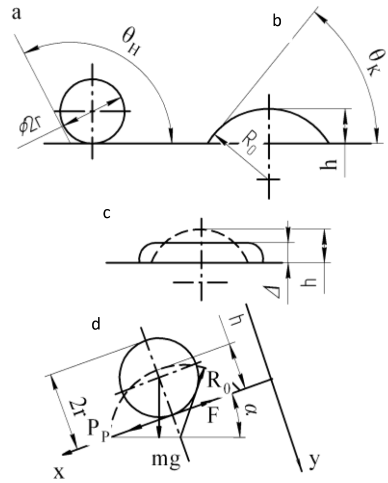

Fig. 1. Design schemes of wetting the surface.

A drop lying on the surface at an angle α to the horizon is affected by: gravity mg и friction force F.

$$mg = \frac{4}{3}\pi r^3 \rho_W g, \quad (1)$$

$$F = \mu S \frac{dV}{dy}, \quad (2)$$

where r – reduced drop radius; ρ_W – density of liquid (water); μ – viscosity of the liquid; $\frac{dV}{dy}$ – velocity gradient over the height of the layer area S.

Given the surface tension, the spreading force is determined from the expression:

$$PP = a1\, r\sigma(1-\cos\theta), \quad (3)$$

where σ – surface tension coefficient; θ – wetting edge angle.

The general equation of droplet spreading over the surface has the form:

$$\frac{d(mV)}{dt} = mg\sin\alpha + P_p - F, \quad (4)$$

During evaporation, the radius of the drop and, accordingly, its surface area decrease S=a1r2.

where a1 – coefficient that takes into account the change S and r. For a spherical drop a1max= 4π.

Edge angle θ the initial stage of spreading θH (θHmax = π), final – θK.

Then:

$$P_{cp} = \frac{a_1 r\sigma \int_{\theta_H}^{\theta_K}(1-\cos\theta)d\theta}{\theta_H - \theta_K} = a_1 r\sigma\beta, \quad (5)$$

where β – the coefficient of change in the shape of the drop (0<β≤1)

$$\beta = \frac{\int_{\theta_H}^{\theta_K}(1-\cos\theta)d\theta}{\theta_H - \theta_K}, \quad (6)$$

In general, when $\theta_H \neq \pi$, $\theta_K \neq 0$

$$\beta = 1 - \frac{\sin\theta_K - \sin\theta_H}{\theta_H - \theta_K}, \quad (7)$$

With full spreading $\theta_H = \pi$, $\theta_K = 0$

$$P_{cp} = 2\pi\, r\, \sigma, \quad (8)$$

For solutions $\theta_K \neq 0$, then

$$P_{cp} = 2\pi\, r\sigma\beta, \quad (9)$$

Theoretical dependence $\beta = f(\theta)$ shown in Fig. 2.

The wetting spot of a drop can be determined from the equality of volumes (initial and final).

$$\frac{\pi d_K^3}{6} = \frac{\pi \ell^2}{4}\Delta, \quad (10)$$

where ℓ – the size of the wetting spot after spreading the droplet to a thickness of Δ.

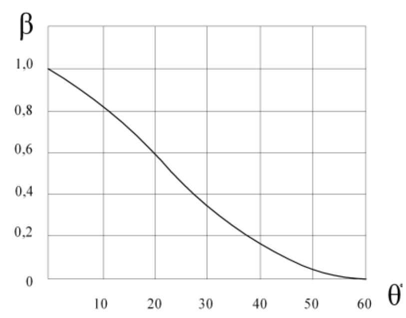

Fig. 2. Theoretical dependence of the coefficient β on the wetting angle θ.

Then:

$$\ell = \sqrt{\frac{2d_K^3}{3\Delta}}. \quad (11)$$

For wetting forest combustible materials when creating a barrier strip, a minimum layer of liquid is required Δ:

$$h_{CP} > \Delta, \quad (12)$$

where h_{CP} – liquid film thickness.

To achieve a critical level of moisture content, the thickness of the liquid film should be at least 0.1 mm.

Considering that the operator's movement speed is constant (VP=const) [16]:

$$h_{CP} = \int q(L)dt = \int q(L)\frac{dL}{V_p}, \quad (13)$$

$$V_p h_{CP} = \int q(L)dL, \quad (14)$$

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where q – performance of a knapsack forest fire extinguisher, l/min; V_P – the speed of movement of the operator, equal to the speed of extinguishing the edge of the fire, m/ min; L– the length of the edge of a grass-roots forest fire, m.

Let's consider the efficiency of the process of direct extinguishing of fires with a sprayed liquid.

The uniformity of the distribution of the liquid layer on the forest combustible materials, the linear intensity of the supply, the consumption of the extinguishing agent, the speed of movement of the operator with a knapsack forest fire extinguisher are of great importance for optimizing the technology of extinguishing fires. Linear intensity of water supply refers to the amount of water supplied per unit of time per unit length of the edge of a grass-roots forest fire.

In the tables 1 and 2 the average statistical data on the rate of extinguishing the edge of grass-roots forest fires with a satchel forest fire extinguisher RLO-M, depending on the intensity of the fire and water consumption, are given [17].

Table 1. The rate of extinguishing the edge of a low-level fire, m/hour.

Type of grassroots fire	Fire intensity		
	high	average	grassroots
stable	20-40	40-80	80-150
runaway	30-50	50-100	100-200

Table 2. Water consumption when extinguishing the edge of a grass-roots forest fire with a length of 1m using a RLO-M.

Type of grassroots fire	Fire intensity		
	high	average	grassroots
Water consumption, l/m			
stable	5.7-2.8	2.8-1.4	1.4-0.7
runaway	3.8-2.3	2.3-1.1	1.1-0.5

Linear intensity I′ and the time of its submission τ when extinguishing the edge of a grass-roots forest fire with a length of 1 m:

$$I' = \frac{q\tau k}{L}, \quad (15)$$

where τ– the time of extinguishing the edge of a forest fire; k– working time utilization factor (k = 0,85).

Then the extinguishing time, min:

$$\tau = \frac{LI'}{qk}. \quad (16)$$

The performance of the RLO-M knapsack forest fire extinguisher is 2.25 l/min. The results of the quenching time calculations are summarized in Table 3.

The effectiveness of fire extinguishing is determined by the correct choice of fluid flow and ensuring uniform distribution over the area.

Table 3. Time of extinguishing the edge of a low-level forest fire with a length of 1m using RLO-M.

Type of grassroots fire	Fire intensity		
	high	average	grassroots
Water supply time, s			
stable	180-90	90-45	45-24
runaway	120-72	72-36	36-18

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The average layer of liquid poured out during the movement of the operator with the RLO-M, m:

$$h_{CP} = \frac{0{,}001q}{BV_P}, \qquad (17)$$

where B – capture width, m; V_P – the speed of movement of the operator, equal to the speed of extinguishing the edge of the fire, m / min.

Practically, the width of the spray torch is determined by the pressure, the angle of the spray and the height of the location relative to the treated surface.

The type of spraying nozzle should also ensure maximum uniformity of the liquid distribution over the area.

Experimental studies are needed to determine the effective width of the jet. The optimal jet width of more than 30 cm will be provided by a torch angle of more than 45˚ at a spraying height of about 40-60 cm.

Let's consider the possible mechanisms of the effect of a jet of water vapor on the combustion processes combustion.

Water vapor is water in a two-phase state. The liquid and vapor phases are in contact with each other and are in a non-equilibrium state. In addition, the temperature of the water vapor jet is below equilibrium. Therefore, the jet of water vapor is accompanied by condensation processes. The intensity of steam condensation is determined by the supercooling temperature, steam density, jet flow rate and environmental parameters. It is necessary to study the characteristics of the jet and evaluate their effect on the combustion process combustion.

A jet of water vapor has a cooling effect on the combustion zone combustion. Heat of combustion is spent on heating of water vapor, evaporation of condensation foci, heating of the formed vapors. The cooling process can lead to a decrease in the intensity of combustion or to its complete cessation.

Water vapors trapped in the combustion dilute combustion concentration of combustible reagents involved in the combustion and oxygen of the air supplied by convective flows. The dilution process reduces the rate of combustion reaction.

Thus, the extinguishing effect of a jet of water vapor on the front of the fire can be realized:

– cooling of the combustion zone;

–dynamic blowing off of combustible pyrolysis products and air oxygen;

–screening of the combustion zone from the heating and pyrolysis zones;

– isolation of the flame torch from the oxygen of the air.

The main design parameters of the steam generator are: length, diameter of the steam generator rod, length of the heating element, the required volume of the water tank, heater power (for an electrical device).

The minimum pressure for converting water into saturated steam is – 0.1 MPa. The maximum pressure is 22MPa. The critical temperature is 374.15 ˚C [18].

For an autonomous mini-installation, we accept:

The volume of water is 8 liters. The created pressure is 0.2 MPa. The diameter of the outlet is 3 mm [18].

For electric mini-installation:

The volume of water we accept is 4 liters. The created pressure is from 0.2 MPa. The diameter of the outlet is 3-5 mm (adjustable) [18].

The limiting factor when setting the volume of the water tank in both cases is the weight.

3 Research results

To conduct research on the possibility of extinguishing forest grass-roots fires with thinly sprayed water, steam, and two-phase media, the following technical means have been developed:

1. A number of spraying nozzles with different spray angle and flow rate have been developed for the RLO-M and Ermak knapsack forest fire extinguisher.
2. Autonomous steam generator mini-installation [16-19].

It consists of two main parts: a heating device and a heat exchanger (Fig.3-4).

The burner 1 of a blowtorch with a tap 2 fixed in the casing is used as a heating device. The flow tank is equipped with a built-in pump 3 for supplying gasoline to the burner under pressure.

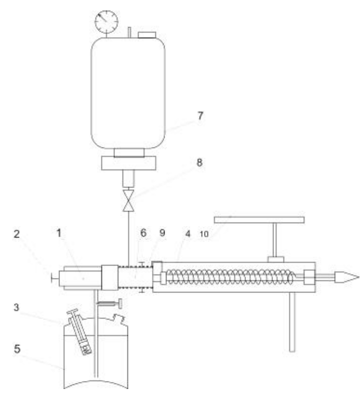

Fig. 3. Diagram of an autonomous steam generator set.

The heat exchanger is a device consisting of a metal casing 4, a piping system and a flow tank 5. The casing is made in the form of a steel pipe with a diameter of 60 mm, a length of 500 mm, with a built-in mounting device 6 for the burner and a hole for air intake. The water supply tank 7 is designed for a volume of 8 liters.

The outlet pipe of the water supply tank through the valve 8 and the hose is connected to a copper tube 9 wound on the casing and intended for heating water. The inner diameter of the outlet nozzle is replaceable from 2 to 5 mm. For thermal insulation, the heat exchanger casing is coated with asbestos. There is a handle 10 for carrying the installation.

Fig. 4. Autonomous steam generator set, ready for operation (with protective cover and backpack).

To increase productivity and increase the speed of extinguishing fires, an electric steam generator set was developed (Fig. 5-6), including a consumable tank 1, with a filler neck 2, an electric heating element 3, with main 4 and discharge 5 valves. The emergency automatic device 6 is triggered when the temperature exceeds the critical temperature. The

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spraying device is a rod 7, at the end of which a nozzle 8 with a control valve 9 is installed. The installation operates from a generator 10 installed on small vehicles.

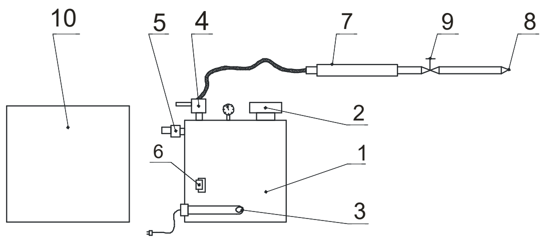

Fig. 5. Electric steam generator set.

Fig. 6. Electric steam generator set.

The consumption of the steam generator was determined by the formula:

$$G_C = 0{,}25D^2\pi w_2\rho_{PP} \quad (18)$$

where Gc – second steam consumption, kg/s; STP – flow cross-sectional area equal to the cross-sectional area of the steam generator pipe or nozzle, m2; ρPP– the density of the working fluid, kg /m3.

The wetting characteristics were determined by treating the surface with clean water and using a wetting agent (20% calcium chloride solution with 0.5% wetting agent OP-7).

The geometrical characteristics of the steam jet, temperature, velocity pressure, steam content in the jet, and condensate mass were also determined. A testo 881-2 thermal imager was used to determine the surface temperature. The multiplicity of tests is from 3 to 5.

The speed of movement of the operator with a source of extinguishing agent (water, steam) was measured. The time of extinguishing the edge of the fire was determined until the complete suppression of the flame combustion.

The results of studies of the edge angles of wetting from the duration of treatment τ with the help of a knapsack forest fire extinguisher RLO-M are shown in Figure 7.

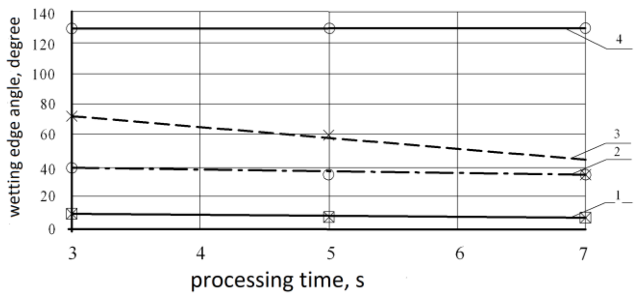

Fig. 7. Dependence of the edge angle on the time of treatment with finely sprayed water: 1–distance from the nozzle nozzle 1m, wetting agent; 2–distance from the nozzle 2m (θ= -τ+43; R2=0.99, wetting agent); 3– distance from the nozzle 3m (θ= -6.25τ+89.5; R2=0.98, wetting agent); 4–water without a wetting agent.

The data obtained indicate that the surface of forest combustible materials is practically non-wettable and water treatment without a wetting agent is low-effective and requires greater intensity. When treating the surface of LGM with an aqueous solution with a wetting agent, the edge angle is smaller than when treated with water and decreases with increasing processing time [18].

The measurement results showed that the temperature at the outlet of the steam generator nozzle is about 75˚C, Fig. 8.

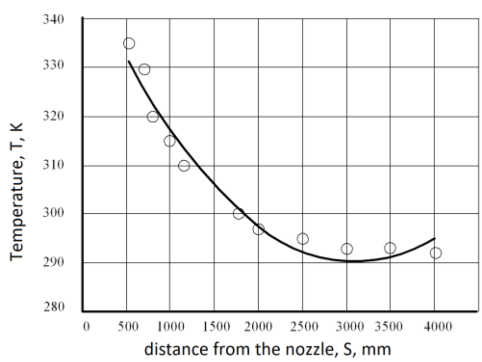

Fig. 8. Dependence of the jet temperature on the distance from the nozzle of the steam generator: T=332.1222-0.0321S+6.1453e – 6S2; R=0.996.

Studies show that the percentage of condensed moisture at the outlet of the nozzle is zero. With the distance from the nozzle, the percentage of the liquid phase increases. When moving away from the nozzle section, intense steam condensation occurs [16], Fig.9.

The thickness of the condensate film depends on the speed of movement of the steam source (Fig. 10).

During subsequent passes, steam condensation no longer occurs on a solid surface, but on a liquid film and a drop of water spreads over the treated surface with a smaller wetting angle, covering a large surface with a thin layer [16].

The task of experimental studies was also to evaluate the mechanisms of interaction of a jet of water vapor with various combustion foci combustion.

Dried pine bars of wood with a moisture content of 9% were used as a combustible material. The air temperature was 20 ° C. Air humidity -80%. The wind speed is not more than 1.5 m/s.

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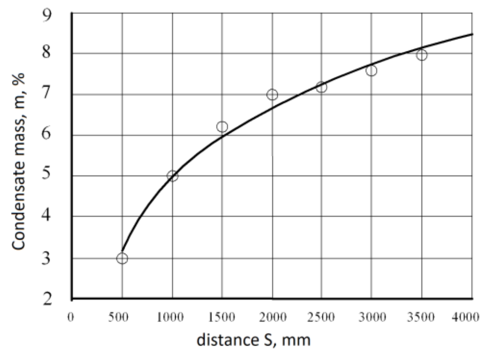

Fig. 9. Estimation of the condensate mass in the steam jet: m% =5.8648 ℓogS -12.6454; R=0.996; R2=0.993.

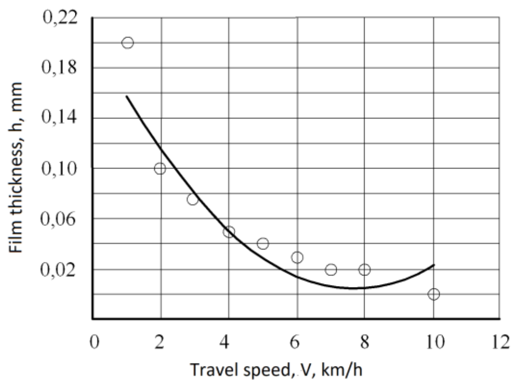

Fig. 10. Dependence of the thickness of the condensate film on the speed of movement of the steam generator: h=0.2067-0.0527V+0.0034V2; R2=0.93.

With a short-term exposure to steam on the hearth, diffusion combustion stopped. If heterogeneous combustion had time to develop before the start of extinguishing, then after a short-term exposure to steam, in half of the cases, flame burning resumed combustion.

The condition for stopping the burning of wood is the cessation of flame combustion and cooling of coals formed during combustion to a temperature below the pyrolysis temperature, i.e. below 200 ° C. In the case of heterogeneous combustion, the effect of a jet of water vapor on the centers of smoldering is ineffective.

To cool the diffusion flame torch, a steam consumption of 1.9 kg per kilogram of wood is required.

The water vapor consumption required to dilute the gaseous pyrolysis products formed from one kilogram of wood is about 7 kg.

Thus, the scope of application of steam as a fire extinguishing agent should be limited to the impact on the leading edge of the fire.

Dry grass, branches with a humidity of 7.3%, at an air temperature of 20-22 ° C, wind speeds up to 2 m/s, air humidity -10% were used as a fuel material with a developed structure, Fig. 11.

The effect of a jet of steam and sprayed water on the combustion hearth led to a decrease in flaming combustion. Complete cessation of combustion was carried out in the area of direct exposure to the steam jet – up to 2.0 meters from the nozzle.

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Fig. 11. Extinguishing fires of a complex system with a highly developed surface.

The maximum extinguishing result was when exposed to a steam jet at an angle of 30 ° to the ground surface and at an angle of 30-45 for sprayed water. The effective speed of movement of the operator with a steam source along the leading edge of the fire front is 20 m/min.

4 Conclusions

To reduce the consumption of fire extinguishing agents, in particular water, the following main directions were identified: the correct selection of fire extinguishing agent depending on the extinguishing conditions and the type of forest combustible materials; optimization of the scheme and mode of extinguishing; the use of two-phase media, thinly sprayed water, steam; increased wetting of the surface.

Studies of the operation of the RLO-M knapsack forest fire extinguisher in the mode of atomized liquid supply revealed the relationship between the rate of extinguishing the edge of the fire, water consumption, the intensity of its supply and the extinguishing time. The optimal ratios of the angle of the spray torch, the height of the jet supply and the width of the jet are determined. The considered process of wetting the surface of the forest litter made it possible to determine the wetting edge angle, ways to increase the wetting of a solid surface.

The possible mechanisms of the effect of a jet of water vapor on combustion processes and the process of steam condensation, the properties of two-phase liquids and steam are considered. The main design parameters of the steam generator are selected. The effective speed of the operator's movement when creating a barrier strip is determined based on the process of wetting the LGM surface and the formed condensate layer. The vapor concentration in the air equal to 35% is sufficient to stop combustion.

To conduct research on the possibility of extinguishing forest grass-roots fires with thinly sprayed water, steam, two-phase media, spraying nozzles with different spray angle and flow rate to the RLO-M and Ermak knapsack forest fire extinguisher, as well as autonomous and electric steam generator sets were developed.

The presented experimental studies confirm the effectiveness of sprayed water and steam as independent extinguishing agents and means of creating support strips. To achieve a critical level of moisture content, the thickness of the condensate film should be at least 0.1 mm. The effective velocity of the steam source is about 1.5-2.5 km/h.

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