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EXPERIMENTAL INVESTIGATION OF THE SUPPRESSION OF CROWN AND GROUND FOREST FIRES

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Results of experimental investigations on the suppression of the flame combustion and thermal decomposition of forest combustible materials by aerosol flows of a pure water and aqueous solutions are presented. The characteristics of some sprayers were determined and the densities of wetting of a fire hotbed, provided by them, were calculated. The times of extinguishing hotbeds of model crown and ground forest fires were measured, and distributions of temperatures and heat flows in them were determined. It is shown that the efficiency of extinguishing a forest fire is mainly determined by the sizes of the aerosol droplets acting on it.

Keywords: *crown and ground forest fires, thermal decomposition, fire suppression, water droplets, aerosol.*

Introduction. Tens of thousands of forest fires covering an area from several hundred to several million hectares are recorded annually [1–5]. The elimination of large forest fires is often complicated by the inaccessibility of firefighting areas and their remoteness from water sources. Therefore, today the use of aircraft is one of the most promising and, in some cases, the only possible way of extinguishing forest fires [1–5]. The main problem of using aircraft for extinguishing a forest fire is the large consumption of water and the small coefficient of its useful use. According to the theoretical and experimental investigations [6–8], more than 95% of the water thrown down from a flying vehicle locally to a fire is spent ineffectively, which points to the fact that a special method of spraying of water over a fire zone is appropriate for use in this case. According to the available experimental data [9–11], the droplets of a water thrown down from a flying vehicle can be as large as 3–4 mm in diameter, and it is precisely these large droplets of size no less than 0.5 mm that contain more than 70% of the water thrown down. At the initial instant water droplets fall on the ground surface of a fire zone, a large fraction of them is formed by the droplets of size 1–2 mm. At the next instants of time, the droplets of medium size (0.5–1 mm) become predominant in the fire zone, and then droplets of size 0.2–0.3 mm settle on the ground surface. The dispersity of an aerosol of a water depends on the height from which the water was thrown down: the larger this height, the larger the rate of breakage of the water into droplets [1]. It is believed that a forest fire can be localized and completely suppressed in the case where the average density of the water on its surface is 3–4 L/m^2 [9–11]. However, these conditions are difficult to provide in real practice of extinguishing a forest fire. To improve the technology of firefighting with water as applied to a forest fire, it is necessary to know the physical bases of this process [12–19]. The mechanism of extinguishing combustible materials with water comprises a fairly complex heat and mass transfer between a flame, the surface of a combustible, and the water droplets [7, 8]. However, the main processes determining the efficiency of extinguishing a fire by water can be distinguished. Among them is the evaporation of water droplets in high-temperature gases [20–22].

Modern systems and methods of extinguishing forest fires involve the use of a large number of retardants, phlegmatizers, wetting agents, solutions, and surfactants. Therefore, of interest is to investigate the characteristics of spraying of typical fire-extinguishing liquids (the sizes, the dispersivity, and the velocity of movement of their droplets) over a forest-fire hotbed depending on its type because a fire in a forest can propagate over the crown of its trees and over the forest ground. The efficiency of extinguishing a forest fire with the use of aircraft is determined in many respects by the parameters of the flow of an extinguishing liquid thrown down from a height to a fire hotbed because a part of the droplets of this liquid are carried away by the wind and are lost in the turbulent convective column formed over a fire. The aim of the present work is to experimentally determine conditions necessary for effective suppression of the flame combustion and thermal decomposition

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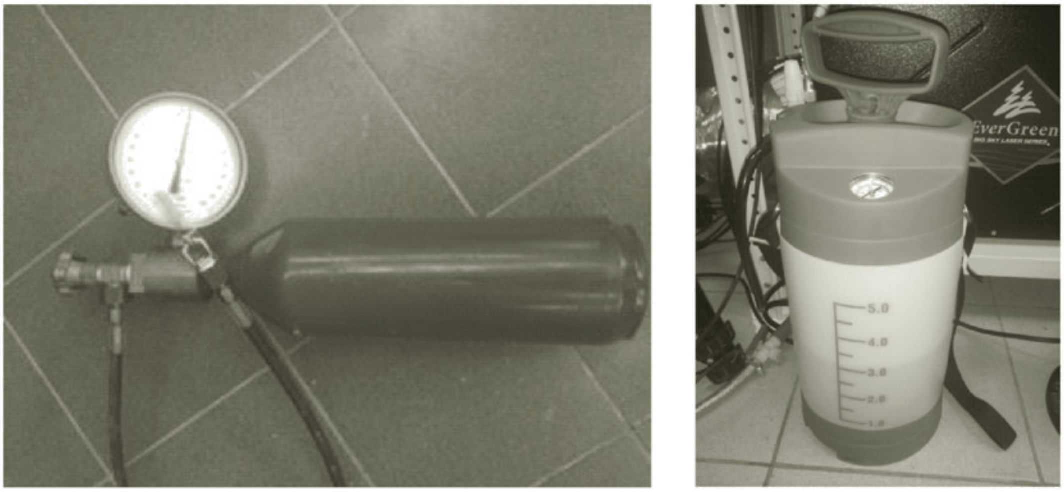

Fig. 1. Reservoir used for generation of liquid droplets.

of forest combustible materials (FCM) in the process of extinguishing hotbeds of model ground and crown forest fires with the use of aerosol flows of a pure water and aqueous solutions.

Experimental Stand and Investigation Method. The experimental investigations were performed in two stages. At the first stage, parameters of different sprayers (the sizes of the droplets generated by them and the velocity of their movement) were determined, and sprayers complying with the requirements of effective forest-fire fighting, determined by the dispersion ability of a sprayer (the sizes of the droplets generated should be as small as 0.2–1 mm) and by the rate of wetting of a FCM provided by it (0.08–0.2 L/(m^2·s) at a definite pressure), were selected. At the second stage, the efficiency of extinguishing hotbeds of model ground and crown forest fires by droplets of different dispersities generated by the sprayers selected at the first stage was determined and the times of extinguishing such fire hotbeds were measured.

The size distribution of the droplets in a spray was determined by the laser diffractometry method with the use of a Malvern Spraytec system [23, 24]. A reservoir of volume 5 L (Fig. 1) was filled with a water, and a required pressure was built up in this reservoir by blowing of a gas (air or nitrogen) into it. Then a sprayer was connected to the reservoir, and water droplets were injected into the region of a laser-diffractometer beam (Fig. 2). The process of water spraying was recorded with the use of high-speed Phantom V411 and Phantom Miro M310 video cameras with a frequency as high as $6 \cdot 10^5$ frame/s and a maximum resolution of 1280 × 1280 pixels, and the frames obtained were processed using special software. Each experiment was analyzed by no less than frames of a sprayed liquid flow. The histogram (V_f) and the cumulative curve (V_c), obtained with the use of the Malvern Spraytec system, are shown in Fig. 3. The sizes of the droplets generated by a sprayer were additionally controlled by the shadow photography method (Fig. 4) based on recording of a shadowgraph of an object having a refraction index differing from the refraction index of the environment [25, 27], and they were calculated using the bubbles identification algorithm (Fig. 5). The velocity of movement of liquid droplets was determined by the PIV (particle image velocimetry) [28, 29] and PTV (particle tracking velocimetry) [30, 31] methods (Fig. 6). The measurement errors did not exceed 3% for the sizes of droplets and 6% for the velocity of their movement. The initial temperature of liquid droplets was about 25^{o}C, and it was measured by a thermocouple completed with a digital thermometer. The maximum accidental errors in determining the temperature of a liquid were ±3^{o}C. By the results of the first stage of experimental investigations, the dispersity of the droplets generated by each sprayer and the velocity of their movement at a certain pressure were determined.

The first series of experiments was conducted in a laboratory equipped with a dry pipe sprinkler system for supply of water, into which a sprayer was integrated. Under the sprayer, a combustible was positioned in accordance with the spraying scheme. The experiments were performed with fire hotbeds of the type 0.7A in accordance with the State Standard R 51057–2001. Such a fire hotbed was positioned at a distance of 1 m from the center of the sprayer. Within 7 min after a FCM was fired, water was supplied to it through the sprayer. The process of extinguishing a fire hotbed was recorded with the use of two video cameras. After the flame combustion of the FCM was suppressed, which was observed visually, the supply of water to it was terminated. A fire hotbed was considered as extinguished if it was not ignited repeatedly within 10 min after the supply of water to it was terminated. Three experiments were performed with each sprayer. From the results of these experiments, a sprayer providing a minimum time of extinguishing a model fire hotbed was selected.

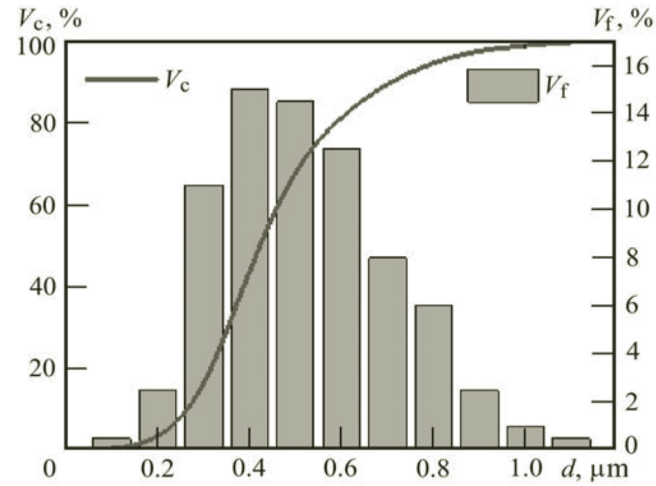

Fig. 2. Measuring Malvern Spraytec system: 1) He–Ne laser; 2) collimated optics; 3) droplet flow; 4) Fourier lens; 5) detector based on silicon diodes; 6) high-speed system for data collection.

Fig. 3. Size distribution of droplets obtained with a Malvern Spraytec system.

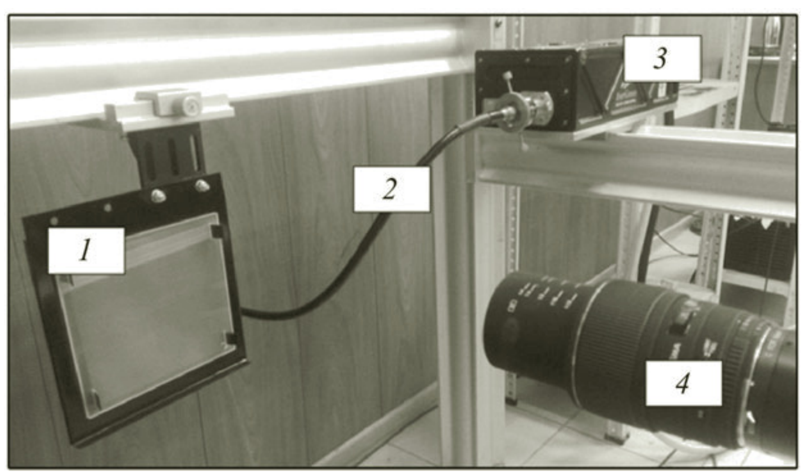

Fig. 4. Equipment used for realization of the shadow photography method: 1) diffusion screen; 2) optical light guide; 3) double-mode pulsed Nd:YAG laser; 4) cross-correlated CCD video camera.

The second series of experiments was conducted on an experimental stand with a transport tunnel equipped with a dry pipe sprinkler system. The hotbeds of model ground and crown fires were selected in accordance with the State Standard R 51057–2001 by the heat energy generated by them compared to that of a real forest fire. A model crown forest fire comprised five staggered fire hotbeds of the type 1A (Fig. 7a). The sizes of such a fire hotbed were 2.5 × 2.5 m, its area was 6.25 m^2, the specific fire load provided by the fire hotbed was 24 kg/m^2, and the heat energy generated by it was 2 MW/m^2. These characteristics correspond to the reference data on the heat energy released in a crown forest fire (as high as 7 MW/m^2). A model forest ground fire comprised seven fire hotbeds of the type 0.1A (Fig. 5b), six of which formed a rectangle of size 2.2 × 2.2 m, and the seventh fire hotbed was positioned at the center of this rectangle (Fig. 7b). The area of such a fire hotbed was 4.84 m^2, the specific fire load created by it was 3.6 kg/m^2, and the heat energy generated by the fire hotbed was 386 kW/m^2. These characteristics correspond to the reference data on the heat energy released in a real ground fire (310–2270 kW/m^2).

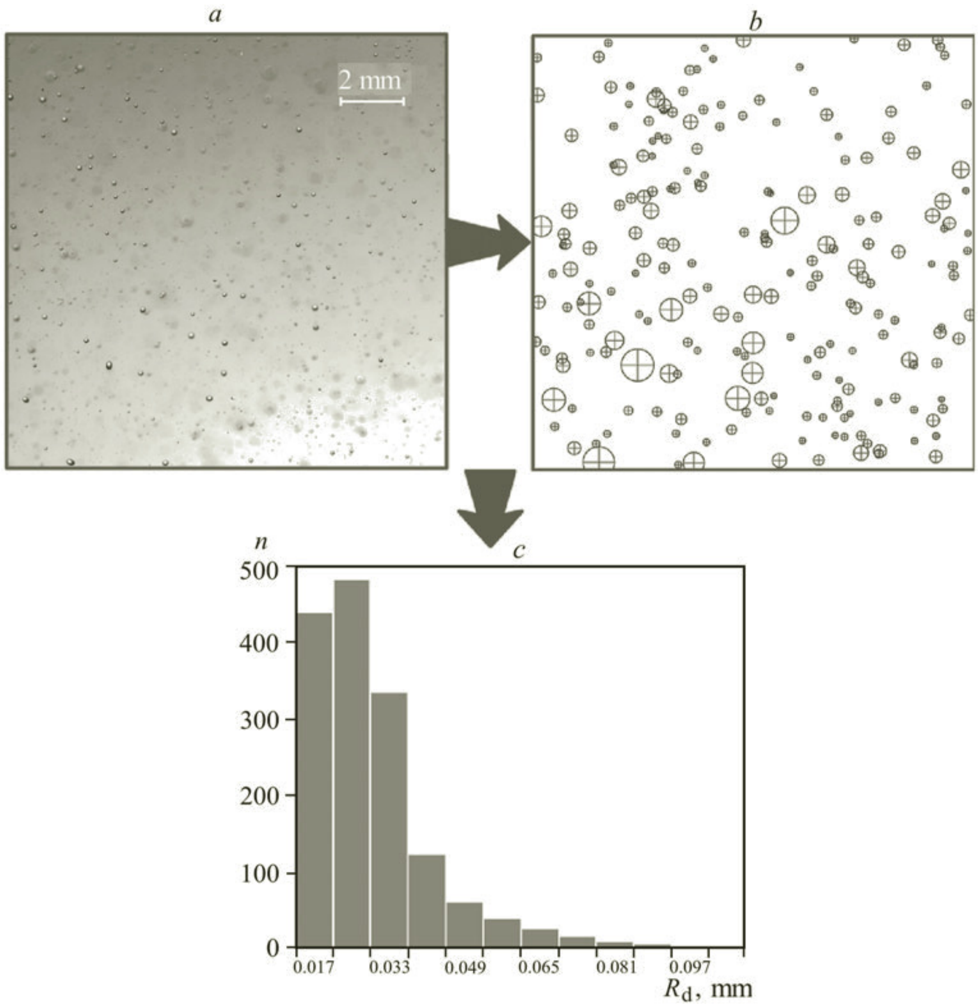

Fig. 5. Images of a droplet flow obtained with the shadow photography method (a, b) and size distribution of the droplets in it (c).

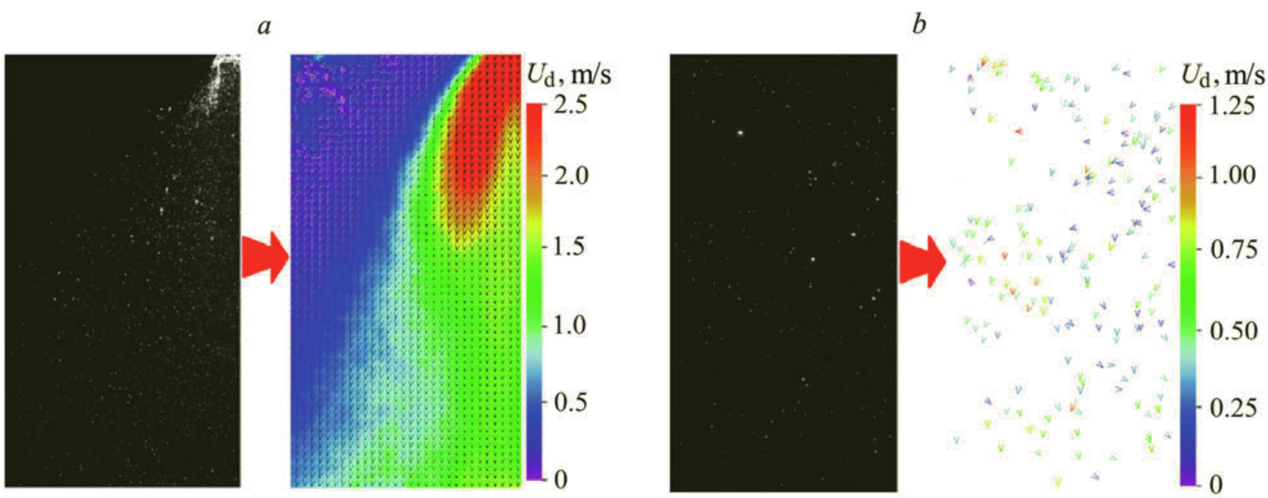

Fig. 6. Videograms of the kerosene combustion products with droplets of the water sprayed at the input (a) and output (b) of a cylindrical channel, processed by the PIV (a) and PTV (b) methods.

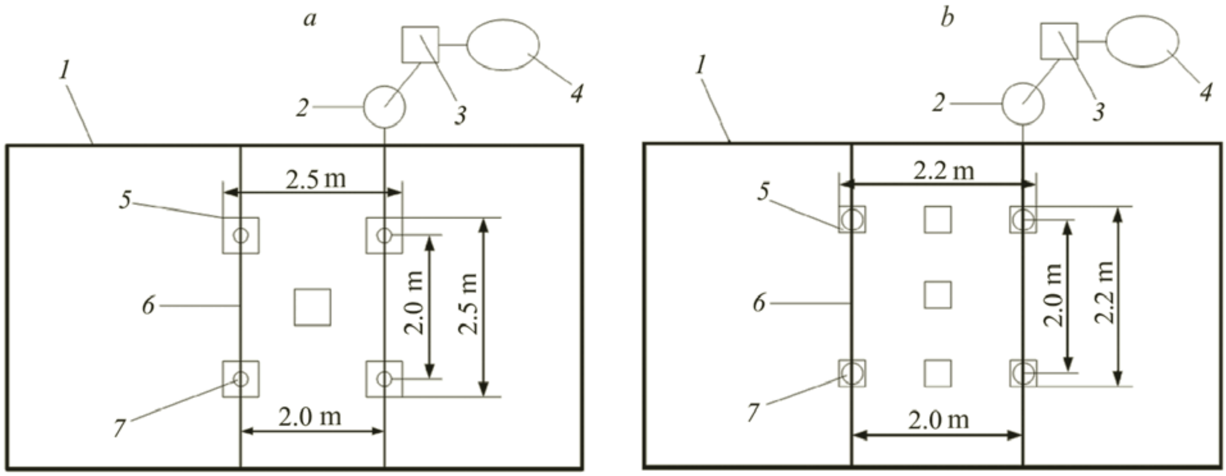

Fig. 7. Diagram of disposition of model crown fire (a) and ground fire (b) hotbeds: 1) transport tunnel; 2) manometer, slop valve; 3) engine-driven pump; 4) vessel with a solution; 5) fire hotbed; 6) dry pipe sprinkler system; 7) sprayer.

In an experiment, a hotbed of fire was placed in the transport tunnel positioned under a distribution pipeline into which sprayers, selected from the results of the first series of experiments, were built in. The number of sprayers was determined with regard for their characteristics. A FCM was ignited in accordance with the State Standard R 51057–2001. In the experiments with hotbeds of a model crown fire, a pure water and aqueous solutions of a grain bischofite (mass concentration 8%), a Krilak-Les wetting agent (mass concentration 20%), and a Firex wetting agent (mass concentration 0.3%) were used. The hotbeds of a model forest ground fire were suppressed with the use of a pure water. A fire extinguishing liquid was supplied to the system of pipelines with the use of an engine-driven pump and an opening unit. This pump provided the intake of the fire-extinguishing liquid from the opening unit and the supply of it to the system of pipelines at a definite pressure. The opening unit represented a plastic vessel of volume 1 m^3. The moisture content of the FCM bars was 4%, and it was controlled with the use of a BSKM-124 apparatus. The temperature in a combustion zone was neamsured by three thermoelectric temperature transducers (TETT) representing chromel–alumel thermocouples (ChAT) made of a KTK 0.11–0.5 wire. One thermocouple was placed in a hotbed of fire, and the two other screened thermocouples, cooled by water, were positioned at distances of 3 and 6 m from the fire hotbed. A diagram of disposition of the thermocouples is shown in Fig. 8. Results of measurements of temperatures in experiments are presented in Fig. 9a. The maximum temperature of the gas in a fire hotbed was 700^{o}C. The indications of the screened thermocouples positioned at distances of 3 and 6 m from a fire hotbed were 100 and 30^{o}C, respectively. The density of the heat flow generated by a fire hotbed was measured by three temperature-sensitive elements (TSE) positioned at a height of 0.5 m in the tunnel and at distances of 3, 4.5, and 6 m from the fire hotbed. A diagram of disposition of these elements is shown in Fig. 6. Results of measurements of heat flows are presented in Fig. 8. The maximum densities of the heat flows found at distances of 3, 4.5, and 6 m from a fire hotbed were 4.5, 2, and 0.75 kW/m^2, respectively. The density of the liquid sprayed over a FCM was determined with the use of measuring vessels in accordance with the State Standard 51043–2002. The uniformity coefficient of spraying of a FCM was K_{spr} = 0.0534 with a roof-mean-square deviation S = 0.01409. Results of measurements of the rate of wetting of a fire hotbed with water are presented in Fig. 10.

Results and Discussion. From the results of the first series of experiments, three sprayers, generating liquid droplets of diameter 0.2–1 mm and providing the rate of wetting of a FCM 0.08–0.2 L/(m^2·s) at a definite pressure, have been selected. In deciding on these sprayers, experimental data on the throw-down of water from an IL-76 airplane [9–11] were taken into account. The sprayers selected had the following parameters: k = 0.217 at P = 0.6 MPa (an Akvamaster-Arsenal sprayer), k = 0.47 at P = 0.2 MPa (a Spetsavtomatika SVN-12 sprayer or SVN-12 sprayer), k = 0.84 at P = 0.15 MPa (a Spetsavtomatika SVN-K160 sprayer or SVN-K160 sprayer). Results of investigations on the spraying characteristics of the indicated sprayers are presented in Fig. 11.

An analysis of the data obtained on the dispersity of the water droplets sprayed by the sprayers selected has shown that the main part of these droplets had a diameter of 460–1000 μm (60%). Among them, the droplets of size 462–547, 547–647, 647–767, 767–908, and 908–1000 μm comprised, respectively, 13.69, 16.16, 16.58, 1.3, and 10%.

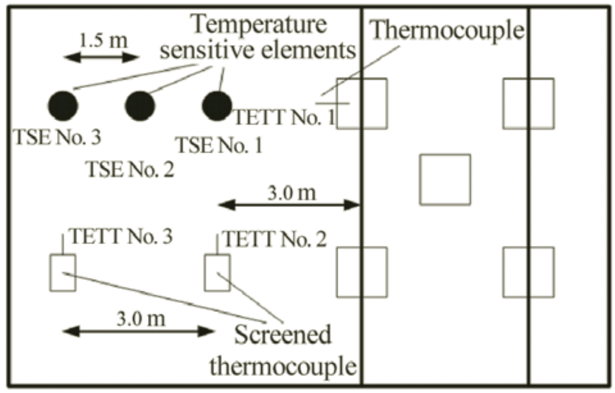

Fig. 8. Diagram of disposition of fire hotbeds and measuring devices.

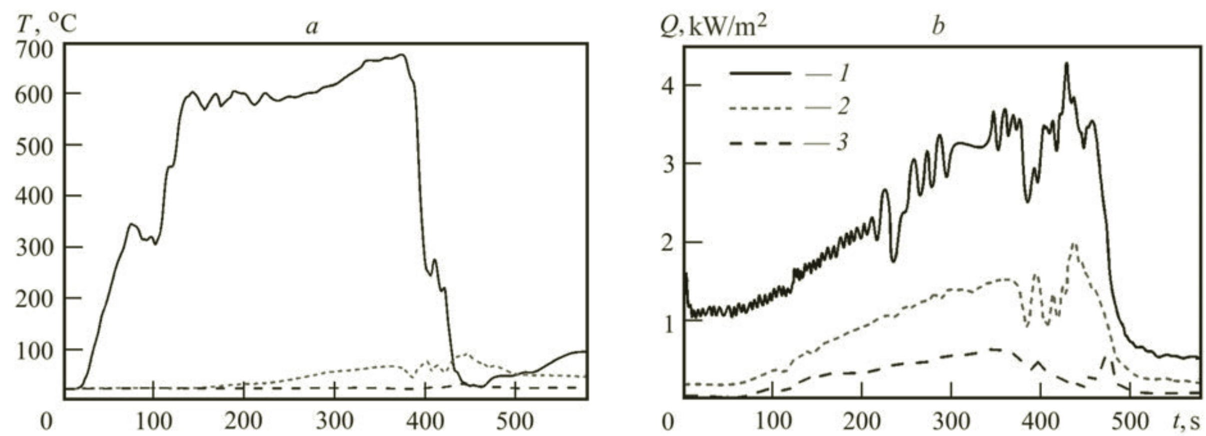

Fig. 9. Results of measurements of the temperature (a) and heat flows (b) in experiments on the suppression of a crown forest fire by water: 1) TSE No. 1; 2) TSE No. 2; 3) TSE No. 3.

Results of investigations on the efficiency of the indicated sprayers are presented in Table 1. In the experiments on the suppression of a 0.7A model fire hotbed with a water, water flows with droplets of average size (radius) 50–500 μm provided a minimum extinguishing time, and a maximum volume of water was required for the suppression of such a fire hotbed in the case where water flows with droplets of size 250–300 μm were used. The data obtained were analyzed with regard for the results of experiments performed in [20, 21].

An analysis of the experimental data obtained (Table 1) has shown that the Akvamaster-Arsenal sprayer generating droplets of size 25–200 μm has a low efficiency with respect to extinguishing a forest fire because droplets of radius $R_d < 150$ μm, travelling only a distance 0.3–0.5 m in the high-temperature (about 800°C) gaseous products of combustion of forest combustible materials, turn around in these gases and are carried away by them [22]. Thus, the indicated droplets cannot reach the surface of a fire hotbed and, therefore, cannot cool it. Droplets of size $170 < R_d < 200$ μm, in their travelling 1 m, equivalent to the distance from a sprayer to the base of a fire hotbed, in high-temperature combustion products, become 50–80% evaporated. At the instant such droplets reach the base of a fire hotbed, their size is decreased to $R_d = 40$–100 μm. These droplets also turn around in the rising flow of combustion products and are carried by it away from the region of combustion of a FCM [22]. Such droplets entering the burning surface of a FCM evaporate almost instantly on this surface, and they have no time to cool it. Therefore, the wetting of the upper part of a FCM practically gives no any effect because the combustion products generated by the burning lower part of the FCM heat its wetted upper layers and aid in the evaporation of the excessive liquid from them.

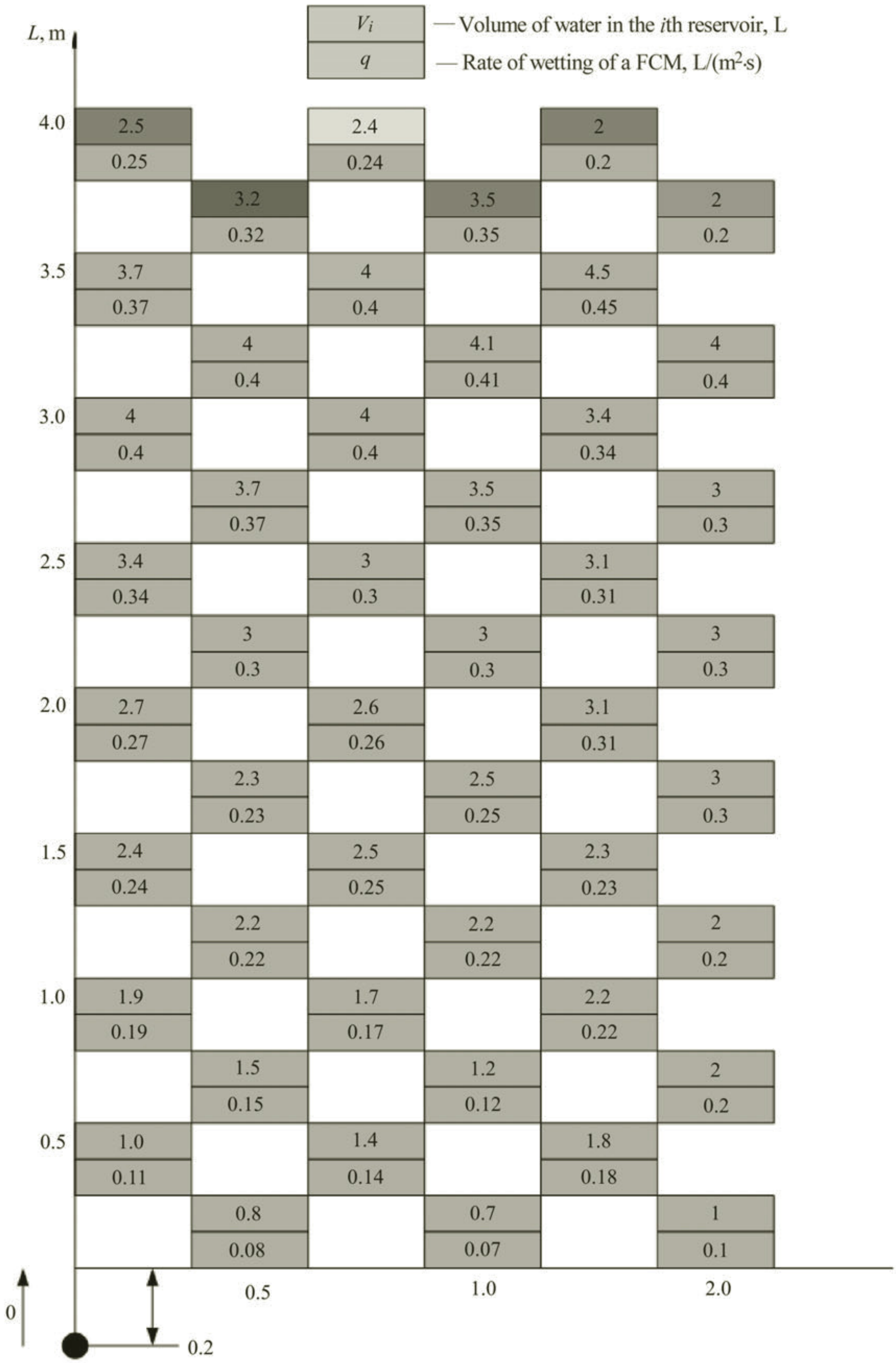

Fig. 10. Results of measurements of the rate of wetting of a model fire hotbed with water at $q_{av} = 0.26396$ L/(m^2·s), $S = 0.01409$, and $K_{spr} = 0.0534$.

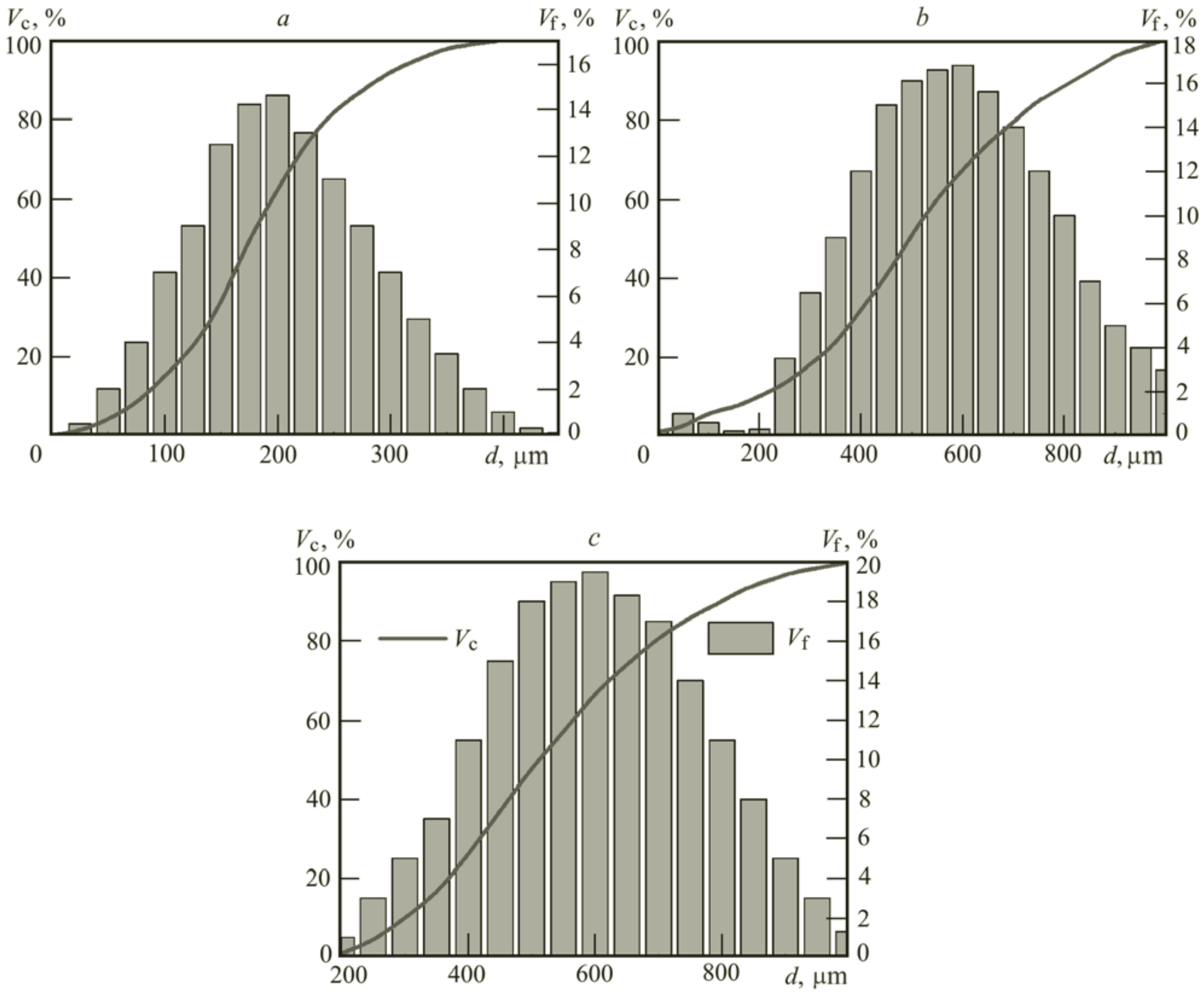

Fig. 11. Dispersity of the droplets generated by the Akvamaster-Arsenal (a), Spetsavtomatika SVN-12 (b), and Spetsavtomatika SVN-K160 (c) sprayers.

TABLE 1. Results of Experiments on the Suppression of a Model Fire Hotbed of the Type 0.7A

Type of sprayer	P, MPa	t_c , s	t_e, s
Akvamaster-Arsenal, $k = 0.217$	0.6	420	Not attained
Akvamaster-Arsenal, $k = 0.217$	0.6	420	Not attained
Akvamaster-Arsenal, $k = 0.217$	0.6	417	Not attained
Spetsavtomatika SVN-12, $k = 0.47$	0.2	420	77
Spetsavtomatika SVN-12, $k = 0.47$	0.2	420	79
Spetsavtomatika SVN-12, $k = 0.47$	0.2	421	85
Spetsavtomatika SVN-K160, $k = 0.84$	0.15	420	427
Spetsavtomatika SVN-K160, $k = 0.84$	0.15	420	435
Spetsavtomatika SVN-K160, $k = 0.84$	0.15	420	440

Results of experiments with the SVN-12 and SVN-K160 sprayers were analyzed with regard for the experimental data obtained in [20, 21]. The average size of the droplets generated by the SVN-12 and SVN-K160 sprayers falled, respectively, within the ranges $20 < R_d < 500$ μm and $150 < R_d < 500$ μm. The results obtained are in good agreement with the results of known experiments where the droplets of size R_d = 170–250 μm were considered as optimum for the suppression of combustion of forest combustible materials. The droplets generated by the indicated sprayers can evaporate by no more than 30–40%. Because of this, they practically do not turn in the combustion products of a FCM and are not carried away by them, which enables them to intensively wet the burning surface of the FCM. It should be noted that, despite the fact that the SVN-12 and SVN-K160 sprayers generate droplets close in size, the times of complete suppression of model fire hotbeds with them are substantially different (Table 1), which can be explained by the difference between the size ranges of the droplets generated by these sprayers: the lower boundary of such a range for the SVN-12 sprayer is R_d = 20 μm, and that for the SVN-K160 is R_d = 150 μm. The upper boundary of the size ranges of the droplets generated by these sprayers is one and the same: R_d = 500 μm. Thus, the presence of small droplets with R_d < 150 μm in a spray is crucial in the suppression of a fire hotbed. Large droplets wet and cool the surface of a FCM subjected to thermal decomposition and, in so doing, gradually decrease the height of a flame and the temperature in the combustion zone, with the result that the velocity of the rising flows of combustion products decreases, which aids in the formation of favorable conditions for the movement of much smaller droplets. Droplets of size R_d < 150 μm evaporate almost completely in their movement through the combustion products of a FCM and, in so doing, decrease the temperature of these products [20]. Since the above-described process is continuous, the water vapor, formed as a result of the evaporation of the indicated droplets, gradually filled the space between the burning bars modeling fire hotbeds, which led to the removal of the oxygen from the combustion zone and to an intensification of firefighting (Table 1). Because of this, the SVN-12 sprayer with k = 0.47 at a pressure of 0.2 MPa was selected for further experiments. This sprayer provided the shortest time of extinguishing a 0.7A fire hotbed of height 5 m. The results of investigations of the dispersity of the droplets different in composition, generated by the SVN-12 sprayer, are presented in Fig. 12.

The experimental data obtained show that the percentage of large droplets in a flow of 20% aqueous-Krilak-Les solution is smaller than that in a pure-water droplet flow: the droplets of size 462, 547, 647, 767, and 908 μm in this solution comprise, respectively, 13.45, 15.67, 15.91, and 9.43%. The percentage of large droplets in a flow of a 8% aqueous-bischofite solution is much smaller: the droplets of size 462, 547, 647, 767, and 908 μm comprise, respectively, 13.11, 14.86, 14.81, 12.47, and 8.57%. The percentage of large droplets in a flow of a 0.3% aqueous-Firex solution is minimum: the droplets of size 462, 547, 647, 767, and 908 μm comprise 11.57, 12.74, 12.6, 10.7, and 7.56%. Moreover, the addition of the indicated substances to the water increases, by an order of magnitude, the content of small droplets of diameter less than 200 μm in a spray of this water, which, evidently, is explained by the fact that the viscosity and surface tension of the water change in this case.

Results of experimental investigations on the suppression of model crown and ground fire hotbeds with the use of the indicated compounds are presented in Table 2. An analysis of these experimental data allows the conclusion that the efficiency of suppression of the flame combustion and thermal decomposition of a FCM is determined, to a large degree, by the spectral composition of a fire-extinguishing liquid and the size of its droplets. In the case where bischofite or Krilak-Les were added to the water, the quality of suppression of the fire with this water was improved insignificantly: the firefighting-efficiency coefficient $K_{eff} = t_{e,w}/t_{e,s}$ was close to unity. It was established that the number of small droplets in sprays of the indicated aqueous solutions is larger compared to that in a pure-water droplet flow, which allows the conclusion that the use of aqueous solutions for extinguishing a forest fire leads, on the one hand, to an excessive consumption of a fire-extinguishing liquid due to the carryover of a part of its droplets by convective flows and the evaporation of droplets [22], and on the other to an increase in the rate of firefighting. Therefore, in deciding on an additive to the water that will be thrown down from a flying vehicle to a forest fire, it is necessary to take into account the viscosity of the substances being considered and select a substance having a higher viscosity compared to that of the other additives to provide the supply of droplets with sizes as large as possible to the surface of a FCM.

To estimate the efficiency of the use of droplets with sizes selected in our investigations, we have conducted additional experiments with fire hotbeds of one and the same type on a proving ground with a wind load. The schemes of ignition of a FCM and suppression of its combustion were identical to the analogous schemes described above. Several experiments have been performed with droplets different in size, with different numbers of sprayers used at a time, and with different arrangements of the sprayers. These experiments have shown that the scheme in which three sprayers wet a fire hotbed on different its sides at a time is most efficient. In this case, the optimum droplet size is equal to R_d = 150–350 μm, and the minimum extinguishing time is t_e = 219 s. We failed to extinguish a model fire hotbed with the use of only one sprayer.

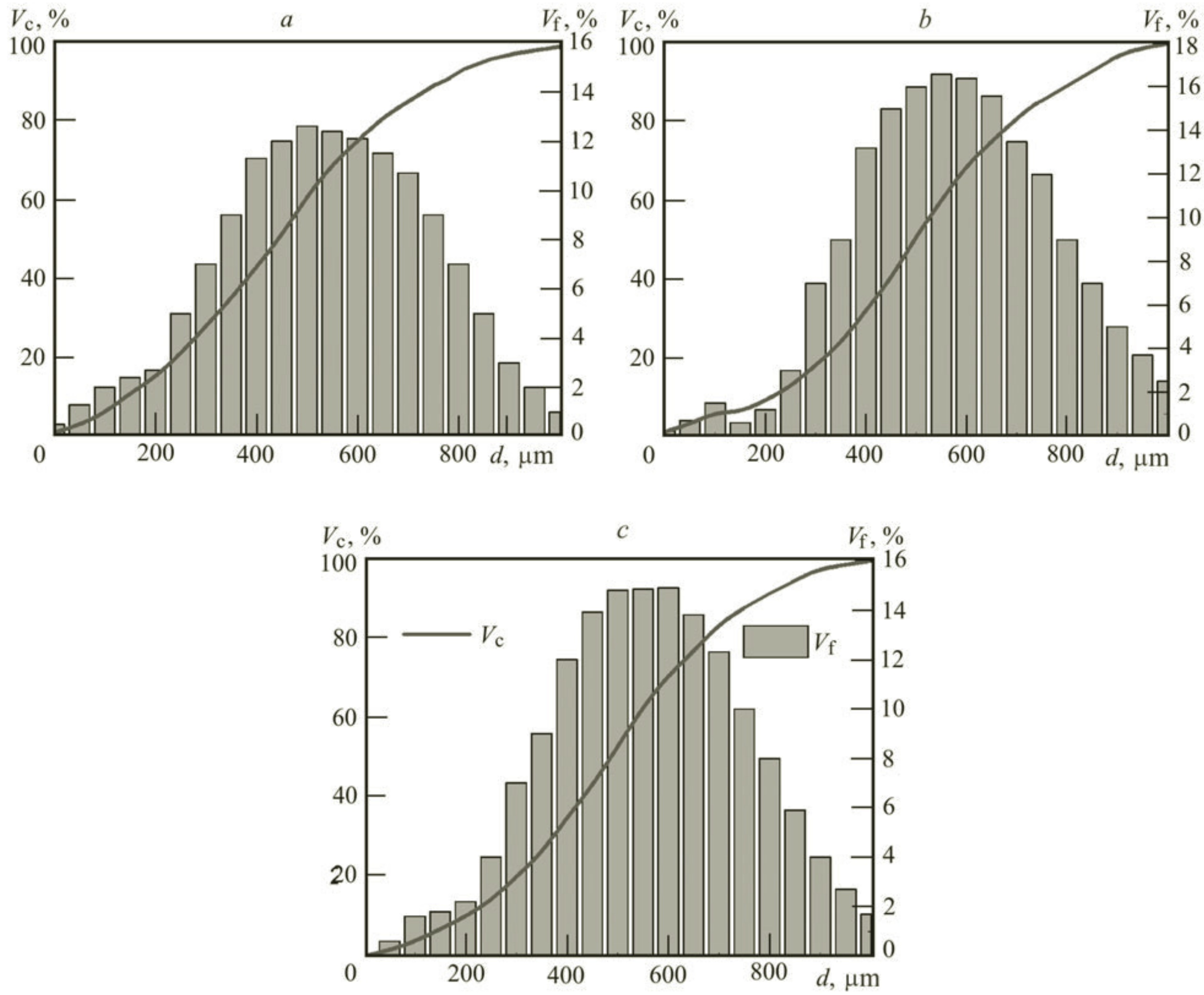

Fig. 12. Dispersity of the droplets generated by the Spetsavtomatika SVN-12 sprayer: a) 0.03% aqueous-Firex solution; b) 20% Krilak-Les solution; c) 20% aqueous-bischofite solution.

TABLE 2. Results of Investigations on the Efficiency of Extinguishing a Forest-Fire Hotbed by Water and Aqueous Solutions with the Use of a Spetsavtomatika SVN-12 Sprayer with k = 0.47 at P = 0.2 MPa

Extinguishing liquid	t_c, s	t_e, s	Type of fire
Water	383	39/52/57/62/80	Crown fire (Five 1A fire hotbeds)
8% aqueous-bischofite solution	353	14/57/63/70/92	Crown fire (Five 1A fire hotbeds)
Water	380	30 (shouldering disappeared within 87 s)	Ground fire (Seven 0.1A fire hotbeds)
Water and 20% Krilak-Les solution	378	48/50/55/56/62	Crown fire (Five 1A fire hotbeds)
Water and 0.3% aqueous-Firex solution	385	60/90 (combustion is in progress)	Crown fire (Five 1A fire hotbeds)

In this case, the flame died out only in the wetted region of a FCM, and droplets were carried over practically instantly from the region of the fire hotbed by the wind, whose velocity reached 2.5–3 m/s. The simultaneous use of three sprayers made it possible to realize a cross wetting of a FCM. The sprayers were arranged so that sprays overlapped and, in so doing, prevented the carryover of small droplets and water vapor, which made it possible to substantially decrease the temperature in the neighborhood of the fire hotbed and remove the oxidizer from the combustion zone. The results obtained as a whole are in good agreement with the results of earlier experiments (Table 1), and they underline the importance of taking into account the direction and velocity of the wind in deciding on the method of extinguishing a forest fire.

The results obtained point to the fact that it is advantageous to extinguish crown and ground fires by sprayed liquid flows. In this case, the main problem is the supply of an extinguishing liquid in the form of droplets of definite dispersity to a hotbed of fire. In the case of local throw-down of a water mass from a flying vehicle, the parameters of such a throw-down necessary for obtaining droplets of required dispersity at the instant they come in contact with a fire hotbed are difficult to forecast. However, the accuracy of this forecast can be increased with the use of known data on the mechanisms of transformation and destruction of large water masses [32]. For example, any liquid mass experiences several stages of transformation in the process of its free fall from a height, with the result that it turns to a cloud with droplets of size from several micrometers to several millimeters and with agglomerates of size as large as several centimeters. In these agglomerates there take place processes leading to their breakage. As a result, after the water mass travels a certain distance, it completely breaks down into small droplets of size from several micrometers to hundreds of micrometers. With the use of the experimental data obtained in [32], one can forecast, with an accuracy as high as several meters, the height of throw-down of a liquid mass providing the breakage of this mass into droplets of required size capable of reaching hotbeds of crown and ground forest fires.

In the case of special spraying of a fire-extinguishing liquid over a fire hotbed with the use of aircraft, of importance is also a knowledge of the parameters of the throw-down of the liquid depending on the velocity of movement of a flying vehicle at the instant the liquid is thrown down from it. If this velocity is high, the density of wetting of the area of a fire will be low, and the throw-down of a fire-extinguishing liquid from a flying vehicle moving with a very low velocity will be accompanied by an excessive consumption of this liquid. The experimental data obtained make it possible to forecast an optimum velocity of movement of a flying vehicle at the instant a fire-extinguishing liquid is thrown down from it; this velocity is 4–5 m/s in the case of extinguishing a crown forest fire, and it is no more than 1.5 m/s for a ground forest fire.

It should be noted that, in deciding on the optimum firefighting parameters (the velocity of movement of a droplet flow, the sizes of droplets, the density of wetting of a FCM) as applied to a crown fire or a ground fire, one should take into account the peculiar features of these fires. For example, the height of a flame in a crown forest fire corresponds to the height of the forest trees. In the case of formation of large convective heat columns in such a fire, the height of a flame can be even larger (10–100 m) than the height of their crowns. Therefore, in deciding on the height of throw-down of a fire-extinguishing liquid and the optimum sizes of its droplets, one should take into account the degree of evaporation of the liquid droplets to provide the conditions under which they can reach a burning surface. The height of a flame in a ground forest fire is, as a rule, no more than 2–2.5 m. In this case, the determination of the height of throw-down of a fire-extinguishing liquid is not a complex problem. However, it is necessary to take into account the type of a forest and the characteristics of the forest litter. Different forest combustible materials burn differently: fallen pine needles and small twigs decompose with intensive heat release, and fallen leaves burn at a lower temperature, but their thermal decomposition can proceed for a longer time. Moreover, the time of extinguishing a forest fire and the volume of a fire-extinguishing liquid necessary for this purpose are dependent substantially on the type of the FCM forming the base of the ground cover in the forest. Different forest combustible materials can contain different amounts of water in their pores. The excessive liquid infiltrates through the hollows in a material and enters the ground. Because of this, the suppression of a ground fire in a forest, whose cover is formed mainly by porous forest combustible materials (twigs, pine needles), calls for an amount of a fire-extinguishing liquid per unit area of the forest cover that is 1.5–2 times larger than that necessary for the suppression of the combustion, e.g., of leaves that are capable of containing a liquid in their layer, which aids in decreasing the required amount of a fire-extinguishing liquid. These facts are of great importance in determining the density of wetting of a FCM in a ground forest fire.

Conclusions. A series of experiments on the suppression of hotbeds of model crown and ground forest fires with the use of a pure water and different aqueous solutions has been performed. These experiments have shown that the processes of extinguishing forest fires with the use of aircraft can be simulated under laboratory conditions. A model crown forest fire with five 1A hotbeds of size 2.5 × 2.5 m and area 6.25 m^2 with a specific fire load of 24 kg/m^2 and a specific heat-energy release of 2 MW/m^2 was suppressed by a pure water approximately within 80 s at a rate of wetting of a FCM of 0.26 $L/(m^2{\cdot}s)$, and a model ground forest fire with seven 0.1A fire hotbeds of size 2.2 × 2.2 m and area 4.84 m^2 with a specific fire load of 3.6 kg/m^2 and a specific heat-energy release of 386 kW/m^2 was suppressed by a pure water approximately within 30 s at a rate of wetting of a FCM of 0.26 $L/(m^2 \cdot s)$. The use of a water with different additives as a fire-extinguishing liquid made it possible to somewhat increase the efficiency of extinguishing a fire compared to that of the pure water. In the experiments with a model crown forest fire, the temperature and density of the heat flows in the fire hotbeds were measured. The maximum temperature in a fire hotbed was 700^{o}C, and the readings of the screened thermocouples positioned at distances of 3 and 6 m from this hotbed were 100 and 30^{o}C. The maximum density of a heat flow at a distance of 3 m from a fire hotbed was 4.5 kW/m^2, and the maximum densities of heat flows at distances of 4.5 and 6 m from the fire hotbed were, respectively, 2 and 0.75 kW/m^2. Our experiments have shown that the efficiency of extinguishing a forest fire is substantially dependent on the composition of a liquid used for this purpose and the sizes of its droplets. In the case of extinguishing a forest fire with the use of aircraft, substances having a high viscosity should be used as additives to a water to provide the obtaining of large droplets capable of reaching the ground cover of a forest and to decrease the number of droplets carried away by combustion products from a reaction zone to a minimum.

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NOTATION

d, droplet diameter, μm; k, efficiency coefficient of a sprayer; K_{eff}, efficiency coefficient of extinguishing a fire; K_{spr}, uniformity coefficient of spraying of a FCM; L, distance from a sprayer to a fire hotbed, m; n, number of droplets, unit; P, pressure MPa; q and q_{av}, rate and average rate of wetting of a FCM, $L/(m^2 \cdot s)$; Q, heat-flow density, kW/m^2; R_d, droplet radius, mm; S, roof-mean-square deviation; t, time, s; t_{com} and t_e, time of combustion of a FCM and time of its extinguishing, s; T, temperature, ^{o}C; T_g and T_w, temperatures of combustion products and water, ^{o}C; U_d, velocity of movement of liquid droplets, m/s; V, volume of water, L; V_c, fraction (cumulative volume) of droplets with a size smaller than the prescribed one, %; V_f, fraction of droplets having a definite size in the total volume of all the droplets in a droplet flow, %; V_i, volume of water in the ith reservoir, L. Subscripts: av, average; c, cumulative; com, combustion; g, gas; d, droplet; e, extinguishing; eff, effective; f, fraction; spr, sprayer; s, solution; w, water.

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