ISSN 0021-8944, Journal of Applied Mechanics and Technical Physics, 2019, Vol. 60, No. 1, pp. 68–79. © Pleiades Publishing, Ltd., 2019.
Original Russian Text © R.S. Volkov, G.V. Kuznetsov, P.A. Strizhak.

EXPERIMENTAL DETERMINATION OF THE FIRE-BREAK SIZE AND SPECIFIC WATER CONSUMPTION FOR EFFECTIVE CONTAINMENT AND COMPLETE SUPPRESSION OF THE FRONT PROPAGATION OF A TYPICAL LOCAL WILDFIRE

R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak

UDC 536.468

Abstract: This paper presents the results of an experimental study of the initiation and containment of the flaming combustion and thermal decomposition of typical forest fuels by creating a fire break in the form of a wet layer of fixed width, length, and depth with a known volume of contained liquid. The ranges of parameter values that ensure stable suppression of the flaming combustion and thermal decomposition of forest fuel material were determined. Experiments were performed for all major types of forest fuels: leaves, needles, branches, and mixtures thereof. The minimum water volumes and fire-break sizes required for guaranteed containment of combustion of the investigated forest fuels are predicted.

Keywords: forest fuels, thermal decomposition, flaming combustion, fire front, containment, suppression, fire break.

DOI: 10.1134/S0021894419010103

INTRODUCTION

The initiation, propagation, containment, and suppression of forest fires have been studied for a long time. The main results of these studies are presented in [1–5]. The need for a comprehensive fundamental study of interrelated heat and mass transfer processes under conditions of thermal decomposition, phase transformations, and chemical reaction is often indicated in papers [6–11]. Results of studies show that modern technologies for forest-fire fighting are not always effective. For example, the consumption of water discharged from the aircraft during one flight can reach 30–50 tons. According to [12–14], in a one-time discharge of such volumes of water, more than 90% of the liquid is spent inefficiently (does not have time to evaporate in the zones of gas-phase combustion and pyrolysis of the material). Effective extinguishing of forest fires requires intense evaporation of water (due to the high heat of vaporization, significant energy absorption is possible) in the region of high-temperature combustion products (in the zone of flaming combustion) [14]. Heat transfer from the combustion zone to the aerosol water flow due to the high specific heat of water also plays an important role. Three regimes of suppression of a typical wildfire take place [15–17]: a decrease in temperature in the combustion zone due to intense endothermic phase transformations; displacement of oxidizer (air) and pyrolysis products from the combustion zone by water vapor; blocking fuel injection into the combustion zone by the forming vapor–gas mixture. A significant synergistic effect can be achieved primarily by the so-called secondary atomization of liquid as it moves through the high-temperature products of combustion and thermal decomposition [15–17].

National Research Tomsk Polytechnic University, Tomsk, 634050 Russia; romanvolkov@tpu.ru; kuznetsovgv@tpu.ru; pavelspa@tpu.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 60, No. 1, pp. 79–93, January–February, 2019. Original article submitted July 25, 2018; revision submitted July 25, 2018; accepted for publication September 24, 2018.

Based on theoretical [12–14] and experimental [16–18] studies, an approach has been developed in which water is sprayed into the combustion zone in a temporarily and spatially distributed mode. Methods of stepwise supply of aerosol portions with droplets of various size have been proposed. The first portion contains droplets with maximum (e.g., 1 mm) sizes, and the last portion has minimum droplet sizes (e.g., 100 μm). The distance between droplets is varied by changing the time interval between aerosol portions. It has been shown [19] that each droplet has a minor effect on the heating and evaporation of the next droplet only if the distance between them is more than (10–12)R_d. This makes practical the temporarily and spatially distributed spraying of water into the combustion zone. This technology requires the use of groups of planes or helicopters which dump water from different heights using special spray systems. Laboratory experiments using fire models have shown [16–19] that this technology can provide almost full utilization (evaporation in the fire zone) of water dumped for fire extinguishing. In particular, it has been established that each subsequent droplet moving in the combustion zone evaporates more slowly (by 30–40%) than previous droplets [19]. As a result, to speed up vaporization in the flaming combustion zone, it is necessary to reduce the sizes of sprayed droplets in each next portion. Furthermore, it should be borne in mind that the flow of high-temperature combustion products decelerates and carries away droplets [16].

A series of physical and mathematical models of heat and mass transfer and phase transformations has been experimentally developed [16–19] to predict the necessary and sufficient amount of water supplied to the combustion zone for effective fire extinguishing. It has been found that approximately 16 liters are sufficient for extinguishing a forest fire with a combustion area of, e.g., 5 × 5 m and 370 liters for a forest fire area of 25 × 25 m [18]. In practice, dozens, sometimes, even hundreds of tons of water are dumped as a rule, on a forest burning area of 500–1000 m^2. In [20], models [12–14, 18] were tested in full-scale, bench or field tests, and in additional laboratory experiments performed to determine the minimum volumes of water needed to suppress the thermal decomposition and combustion of corresponding masses of typical forest fuels.

The results of studies [16–20] led to the conclusion that an important area of fire suppression research is the study of heat and mass transfer processes involving intense phase transformations in the containment and suppression of flaming combustion and thermal decomposition of condensed substances in large areas by applying a special mode of water supply ahead of the combustion front and to the front. Since there are currently no reliable experimental data on heat- and mass-transfer processes and phase transformations occurring during the interaction of a cloud of water droplets with the combustion front under typical forest fire conditions, it is advisable to perform experimental studies of heat-transfer processes during the interaction of droplet water flows with the forest fuel combustion front and to estimate the effect of water aerosol on the suppression of not only flaming combustion, but also the thermal decomposition of typical forest fuels. In addition, it is necessary to investigate the conditions for creating fire breaks in the form of wet layers of materials for forest fire containment [21–25].

Previously [26], studies have been performed using fire models, but no consideration has been given to the size of a fire break (in the form of a wet layer of forest fuels ahead of the combustion front) depending on the wind speed and the structure and main properties of forest fuels. The present study is based on the assumption that the results of experimental studies can be used to predict the size of fire breaks for forest fire areas corresponding to the initial conditions of the formation of combustion fronts. Studies with large-size fire models are impractical since, in this case, it is impossible to reliably determine the required (minimum) amount of liquid for creating fire breaks that needs to be delivered at a time to the forest burning area (full-scale and field tests [20–25] have shown that in practice, additional factors play a role that cannot be excluded). As a first approximation, it is sufficient to perform experiments under laboratory conditions.

The purpose of this study was to experimentally determine conditions for containment of ground forest fire models by creating a fire break with the minimum required size; as in [26], a fire break in the form of a wet layer of forest fuels ahead of the combustion front was considered.

EXPERIMENTAL TECHNIQUE

Materials

As in [20, 26], we used typical forest fuels: birch leaves, pine needles, branches of deciduous trees, and a mixture of these materials (25% birch leaves, 15% pine needles, and 60% branches of deciduous trees). The weight of the samples was 50 g, and their density 0.01838 $\mathrm{g/cm}^3$; the microporosity (calculated from the material particle density) in an absolutely dry state was 0.79 for pine needles and 0.33 for birch leaves.

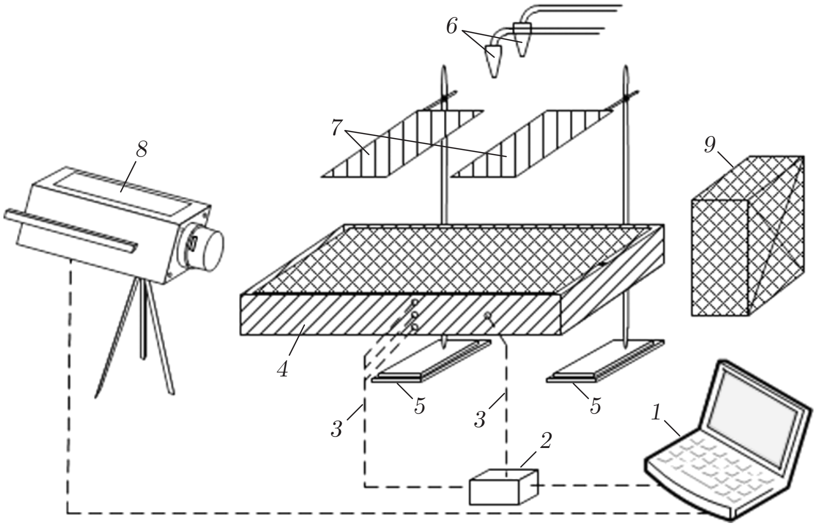

Fig. 1. Diagram of the experimental test bench: (*1*) workstation; (*2*) digital temperature meter; (*3*) thermoelectric converters; (*4*) pan with forest fuel; (*5*) holder; (*6*) nozzles; (*7*) water tank; (*8*) high-speed video camera; (*9*) air injector.

forest fuel samples were pre-dried at a temperature of approximately 300 K for 3–5 days. The moisture content of the materials was determined (by thermal drying) immediately before the experiments. For this, the investigated forest fuel sample was weighed and dried in a drying furnace at a temperature of $T \approx 375$ K for 2–3 h. After the drying, the sample was cooled and reweighed. The relative moisture content of forest fuels was determined by the formula $\gamma = (m_{fw} - m_{fd}) \cdot 100/m_{fw}$, where m_{fw} and m_{fd} are the masses (in kg) of the forest fuels before and after the thermal drying, respectively. The obtained relative moisture contents were $\gamma = 5$–8% for birch leaves, 7–10% for pine needles, and 10–14% for aspen branches; for the mixture of these materials, the relative moisture content was proportional to the content of the components.

The material was placed uniformly in a metal pan (length 310 mm, width 195 mm, and depth 45 mm). Three fast-response Chromel–Alumel thermocouples (range of measured temperatures 223–1473 K; systematic error ±3 K; thermal delay time less than 0.1 s) were located at different levels along the height of the forest fuel sample. Thermoelectric converters were located at a height $H = 5$, 20, and 40 mm from the interface between the forest fuel and the gas environment.

Parameters of the Fire Break

Experimental results for fire burning areas of different sizes and types show that containment of the front pyrolysis is possible only if the transverse size of this front and the length of the fire break coincide. If the length of the fire break was smaller than the transverse size of the pan with the pyrolyzing material, the thermal decomposition front of the latter bypassed the fire break by traveling through the dry surface of the forest fuel and continued to propagate in the area of dry material. Therefore, when analyzing the necessary and sufficient conditions for suppressing forest fuel combustion, it is of interest to determine the dimensions (width and depth) of the fire break.

Experimental Test Bench

Motion of the forest fuel combustion front exposed to water droplet flow was investigated on the test bench [26] shown schematically in Fig. 1. The main objective of the experiments was to reproduce the temperatures ($T \geqslant 780$ K) and heat fluxes ($q = 0.5$–1.5 kW/m^2) that correspond to the combustion of the investigated forest fuels under conditions of forest fires spreading at a moderate (typical [1]) speed (up to 3 m/s).

Table 1. Average discharge intensities at various air flow speeds [26]

Mode of forest fuel–aerosol interaction	U, m/s	ψ, liter/(m$^2\cdot$s)
First	0.5–2.5	0.0500
Second and third	0.5	0.0500
	1.5	0.0375
	2.5	0.0350

Liquid Spraying Modes in the Fire Break

As in [26], three modes of aerosol spraying on the burning forest fuels were considered (Fig. 2).

In the first mode (see Fig. 2a), water droplets flow with fixed discharge density ζ (in each section) and fixed width of the fire break L was created in advance. Then, forest fuel combustion was initiated using piezoelectric burners. The forest fuel sample was fired evenly over the entire free surface. It was assumed that the flaming combustion and thermal decomposition of forest fuel cease if they occur in the zone affected by the liquid aerosol. It was checked that the forest fuel temperature decreased to a value lower than the onset temperature of thermal decomposition (in all experiments, the limiting temperature of the start of pyrolysis was $T_f \approx 400$ K).

In the second mode (see Fig. 2b), water in the form of an aerosol air curtain was supplied directly to the combustion front. At the first stage, forest fuel combustion was initiated. The motion of the combustion front along the forest fuel surface was observed by high-speed video recording. Droplet flow was generated when the combustion front reached middle of the zone covered by the water curtain ($0.5L$).

The third mode (see Fig. 2c) was a combined spraying mode: water was sprayed simultaneously ahead of the front and onto the forest fuel combustion front. In this mode, the liquid aerosol was supply at the moment the flame reached the leading edge of the zone of preliminary action of the droplet flow on the forest fuel ahead of the moving front of forest fuel combustion.

Additional Factors

Experimental results show that in addition to the size of the fire break, the type and properties of the forest fuel, and the temperature in the combustion front, other factors that may have a decisive influence on the conditions of containment and suppression of pyrolysis are the wind speed and the density or intensity of discharge (specific consumption of the liquid).

Typically, the real wind speed does not exceed 2–3 m/s [26]; therefore, in the experiments, this parameter was varied in a limited range (up to 3 m/s). The direction of the air flow coincided with the direction of motion of the combustion front. Air flow was produced by a channel injector of axial type with seven blades (voltage 220–240 V, frequency 50 Hz, power 22 W, air flow rate 320 m^3/h, IPX2 fluid ingress protection). The air flow rate was determined with an anemometer according to the method [26].

Based on the results of experiments [20, 26], we assumed the average discharge intensity ψ for forest fuels depending on air flow speed was accepted. For the first mode of water aerosol spraying on forest fuels, ψ was assumed to be $\psi = 0.05$ liter/(m$^2\cdot$s). The ψ values for the second and third modes depend on the air flow speed U. Table 1 shows the average values of ψ for the investigated modes of the interaction of water and forest fuel for different speeds U.

RESULTS AND DISCUSSION

Main Characteristics of Water Motion through the Forest Fuel Zone

The results of the experiments show that the characteristics of water motion through a layer of typical forest fuels vary widely as the conditions change. These characteristics are significantly affected by the bulk density of the material. and the thermal decomposition, evaporation, and filtration processes, resulting in compaction or, under certain conditions, on the contrary, in an increase in the porosity of forest fuels.

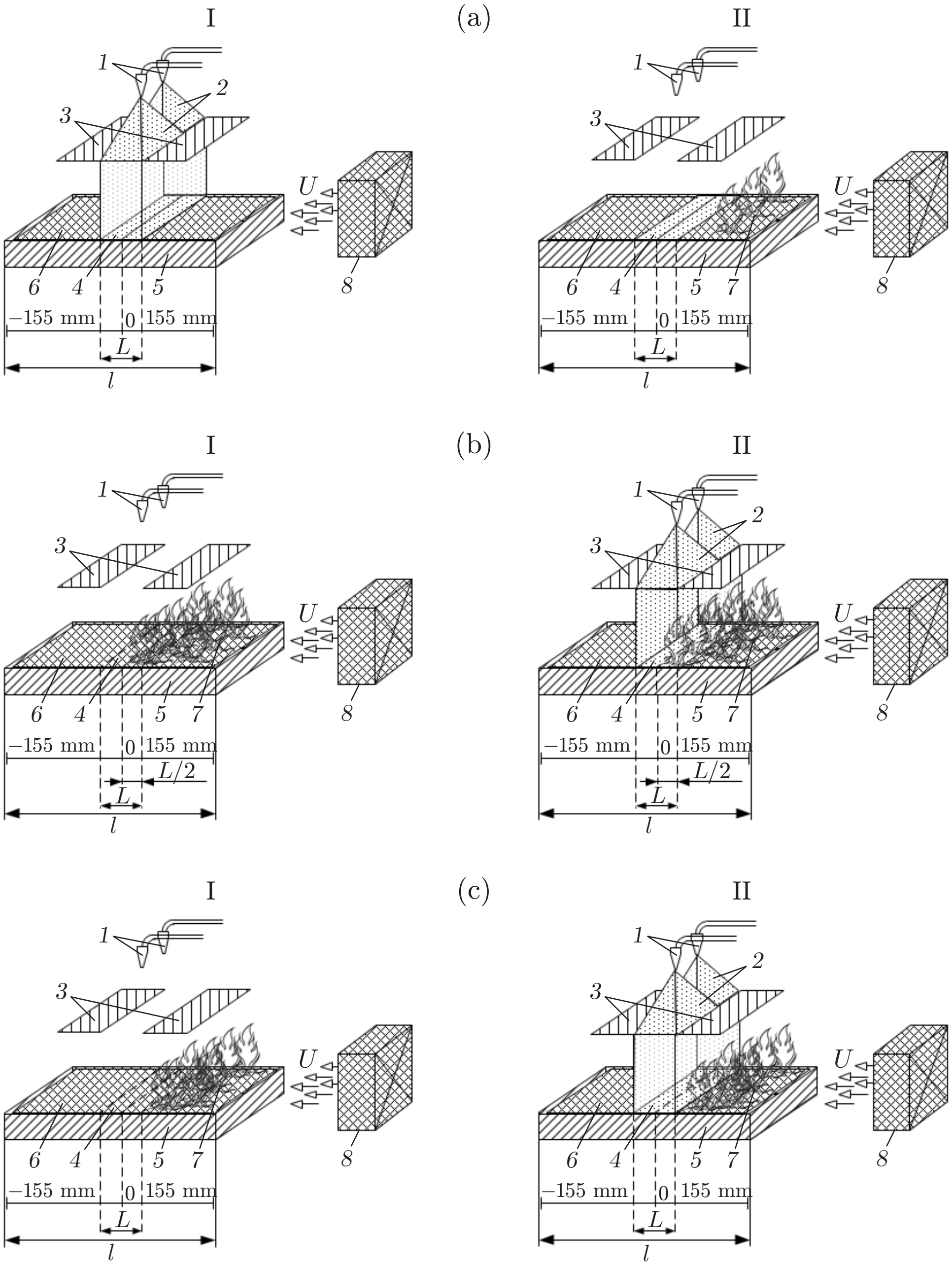

Fig. 2. Water spraying mode [26]: ahead of the front (a), in the front (b), and combined mode (c); (I) first stage; (II) second stage; (*1*) nozzles; (*2*) water aerosol; (*3*) water tanks; (*4*) fire break; (*5*) metal pan; (*6*) forest fuel; (*7*) flame; (*8*) air injector.

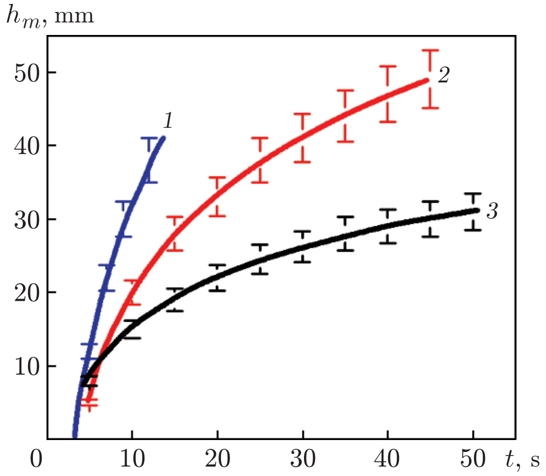

Fig. 3. Water penetration depth in a sample layer versus spraying time: (*1*) pine needles; (*2*) mixture of forest fuels; (*3*) birch leaves.

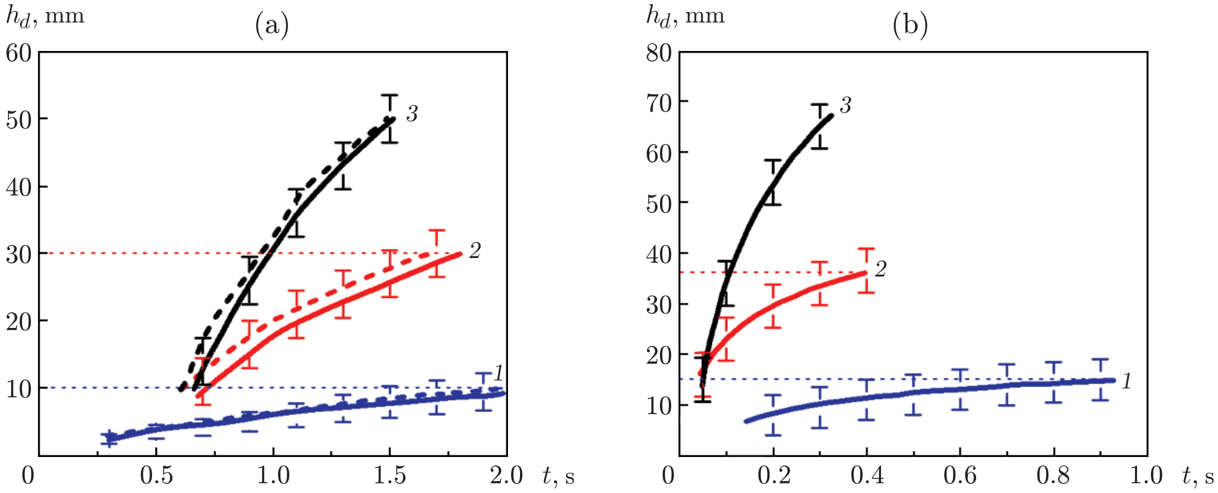

Fig. 4. Curves of the penetration depth of a single droplet in a needle layer sample versus spraying time based on thermocouple measurements (a) and high-speed video recording (b) for $V_d = 90$ (*1*), 200 (*2*), and $V_d = 800$ μliters (*3*); solid curves were obtained in the absence of pyrolysis, and dashed curves in the presence of pyrolysis.

Figures 3 and 4 show time dependences of the depth of penetration of the liquid into a sample layer obtained by high-speed video recording (camera with a frame rate of up to 100 000 s^{-1}) and special algorithms of the Tema Automotive software for tracking moving objects [27]. In the case of intense thermal decomposition, the motion of liquid into the sample was tracked using thermocouple readings [26, 27].

The following regularities can be observed in Fig. 3. Under identical initial conditions (mass, spraying mode, aerosol particle size, etc.), the depths of water penetration into the layers of needles and leaves differ significantly (severalfold). The longer the spraying time and the greater the volume of water used, the larger the difference between the values of h_m in experiments with needles and leaves. This is because the sizes of needles are ten times smaller than the sizes of leaves. Waters droplets spread over the surface of such elements and were held on them in various volumes. When using leaves, the relative resistance to the motion of liquid droplets through

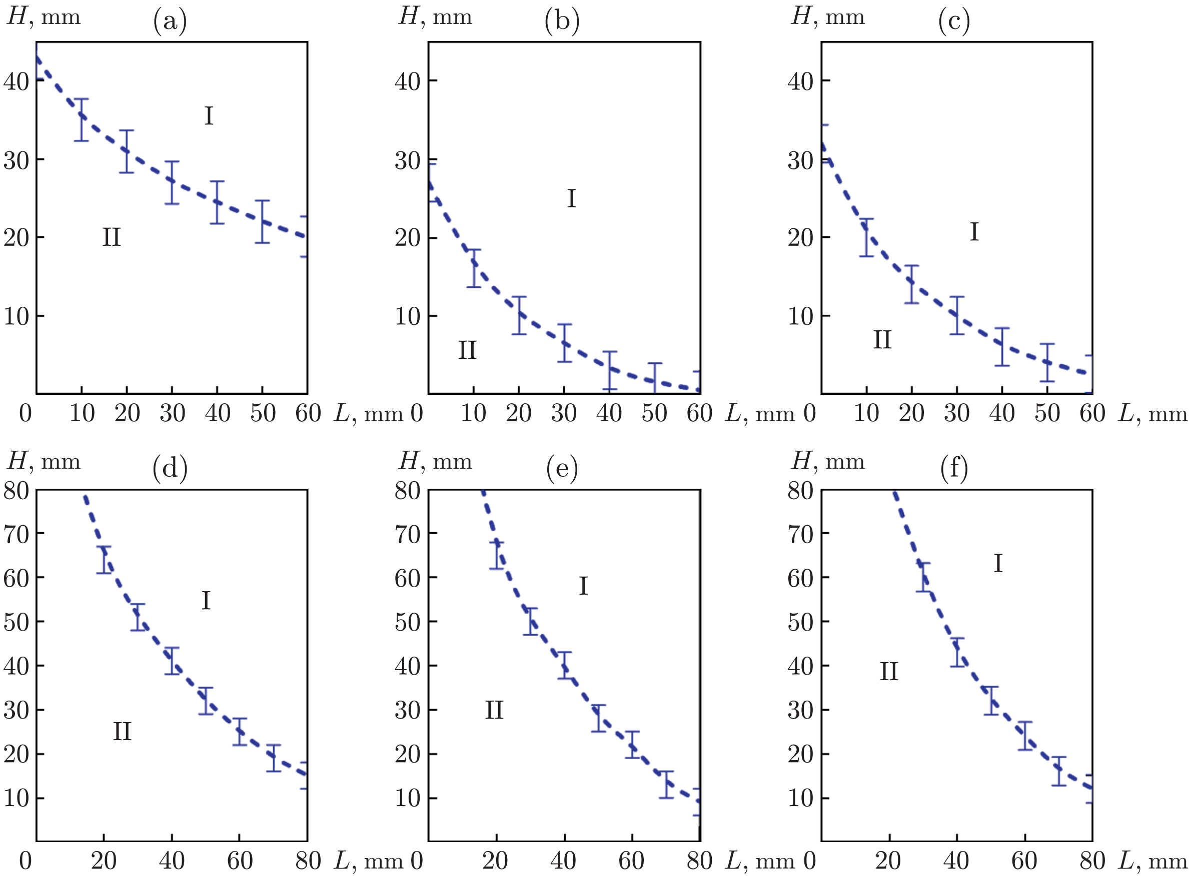

Fig. 5. Regions of containment of fire (I) and combustion (II) at an average wind speed of 1.3 m/s for first mode (a and d), second mode (b and e), and third mode of water spraying into the fire break (c and f): (a–c) birch leaves; (d–f) pine needles; the dashed curve is the boundary between regions I and II.

the sample was much greater. The main mass of water supplied to the forest fuel surface was held in the surface layer or accumulated on the surface of the material and slowly penetrated into the near-surface layers. Thus, we can conclude about intense impregnation (wetting) of only the near-surface leaf layers, penetration of a significant proportion of water into deep layers of needles, and moderate values h_m for the mixture of needles, leaves, and branches.

Pyrolysis has little effect on the speed of penetration of small volumes of liquid through the material sample. However, the greater the volume of water, the more significant the effect of thermal decomposition on the penetration depth. This manifests itself in the fact that the speed of motion of water in the pyrolyzing layers is higher than that in the absence of thermal decomposition because the porosity of the sample material increases during pyrolysis and a large amount of liquid penetrates into deep layers. In addition, in the experiments, compaction of material layers was observed due to intense thermal decomposition and water pressure from above, which accelerated water motion through the sample.

In Fig. 4b, it can be seen that the greater the volume of water entering the forest fuel (or the liquid spraying time at a constant specific consumption), the greater the increase in h_d.

In the absence of intense smoking (observed due to the pyrolysis of compacted forest fuels), the motion of liquid droplets in the sample can be examined using high-speed video recording and thermocouple measurements (a sharp decrease in temperature on one of the thermocouples indicated that the moving water droplets reached the thermocouple). Comparison of the values of h_d obtained using these two techniques shows that they are in satisfactory agreement (on average, the difference is no more than 20%).

Main Suppression Characteristics of Flaming Combustion and Thermal Decomposition of Forest Fuels

In the experiments, we determined the width and depth of the fire break required for containment of combustion of the investigated forest fuels in different modes of water spraying (Fig. 5). As in [26], it was found that the most effective containment of combustion (in terms of the time required to suppress combustion and the volume of water used) can be achieved using the third (combined) mode providing water spraying in both the combustion front (along the edge of the fire) and ahead of it. This speeds up the suppression of flaming combustion and thermal decomposition of the material for all water spraying modes considered.

In experiments with leaves, effective containment is achieved by wetting a sufficiently thin near-surface layer of the sample in the fire break (accordingly, a smaller water volume is required). In the case of needles, combustion containment is possible only by wetting the entire volume of the material in the fire break of (i.e. the depth of the fire break must match the sample thickness) (see Fig. 5). Branches have a high calorific value and a long duration of pyrolysis and, as a consequence, greater heat release; therefore, for effective containment of flame combustion and pyrolysis of branches, it is necessary to increase the time (and hence volume) of water spraying in the fire break.

In experiments with the mixture of forest fuels, similar regularities were observed due to the presence of needles: active thermal decomposition occurred in the forest fuel layer under the fire break (wet material) and behind it, if it was not impregnated (wetted) by water throughout the depth. This is because the motion characteristics of the fronts of burning leaves and needles are different. In particular, the results of thermocouple measurements and high-speed video recording show that thermal decomposition of pine needles occurs with fast motion of the fronts of pyrolysis and flaming combustion not only on the surface of the sample layer in the direction coinciding with the direction air flow motion, but also in deep layers. In a series of experiments, needles were intensely thermally decomposed over the entire depth of the sample layer until the combustion front reached the water line. Therefore, intense pyrolysis of needles occurred both in the near-surface and deep layers of the sample. Obviously, this is due to the fact that pine needles are a highly porous combustible material. As a result, conditions for intense pyrolysis exist over entire depth of the sample layer. In experiments with leaf, intense thermal decomposition was observed only in the near-surface layers. The flaming combustion front reached the fire break with active pyrolysis only in the near-surface layer. Therefore, to slow down the propagation of the fronts of flaming combustion and thermal decomposition of forest fuel in the case of needles, it is necessary to wet the sample throughout the thickness (i.e., increase the depth of the fire break), and in the case of leaves, it is sufficient to wet a relatively thin (20–30% thickness of the sample) near-surface layer (see Fig. 5).

Determination of the Width and Depth of the Fire Break with the Wind Speed Taken into Account

We determined the limit ranges for the widths and depth of the water fire break for the materials studied at different speeds of the air flow simulating wind (Fig. 6). Figure 6 shows three regions of change in the parameters of the fire break corresponding to the cessation or continuation of the motion of the combustion front and to transient conditions (combustion containment occurred with a certain probability or the pyrolysis front overcame the fire break).

The results of the experiments show that the determining factor in combustion containment for almost all investigated materials (to a lesser extent for leaves) is the necessary (minimum) depth of the fire break, which, in turn, depends on the volume of discharged water and the width of the fire break. In the case of leaves, spreading of water over the surface of the sample was observed. Thus, with identical initial volumes of water, the fire break width increased and the depth was less.

Figure 7–9 shows the dependences of the discharge intensity and absolute density on the volume of water, the width of the sample, and the width fire break. It can be seen that in the case of fire breaks formed in accordance with the safest first mode, the water delivery time to the pyrolysis zone does not affect the containment conditions. This is due to the fact that the fire break in the form of a wet layer material is formed in advance, i.e., ahead of the burning front under moderate temperature conditions (corresponding to ambient air). Under such conditions, pyrolysis does not occur. Therefore, the main effect is due to the volume of water and the surface area of the fire break. Consequently, when choosing technological parameters, it is advisable to use the discharge density or specific consumption rather than the discharge intensity. It should also be noted that by varying the volume and mass of the

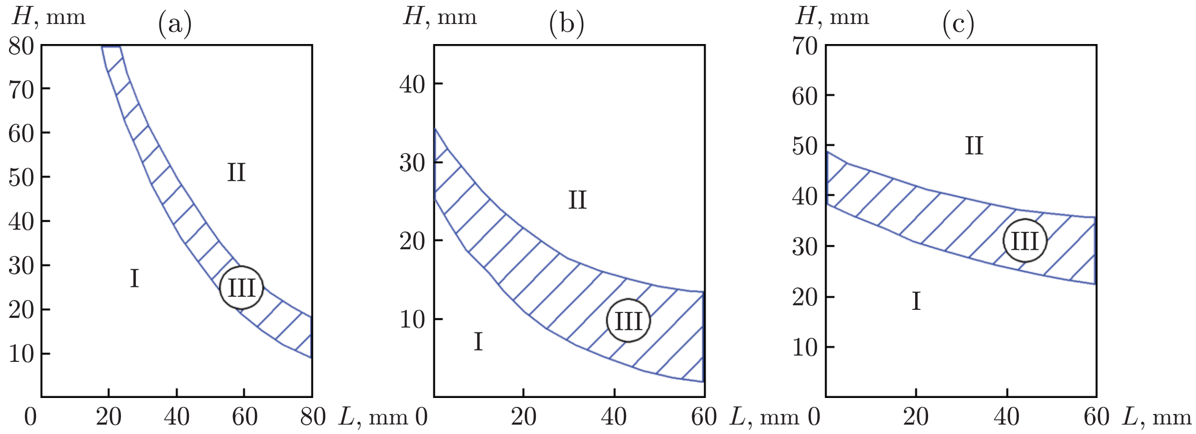

Fig. 6. Combustion region (I), region of containment and suppression of flaming combustion and pyrolysis of the material (II), and a transition region (III) at a wind speed of 0.5–3.0 m/s for the third mode of spraying water into the fire break: (a) birch leaves; (b) pine needles; (c) mixture of forest fuels.

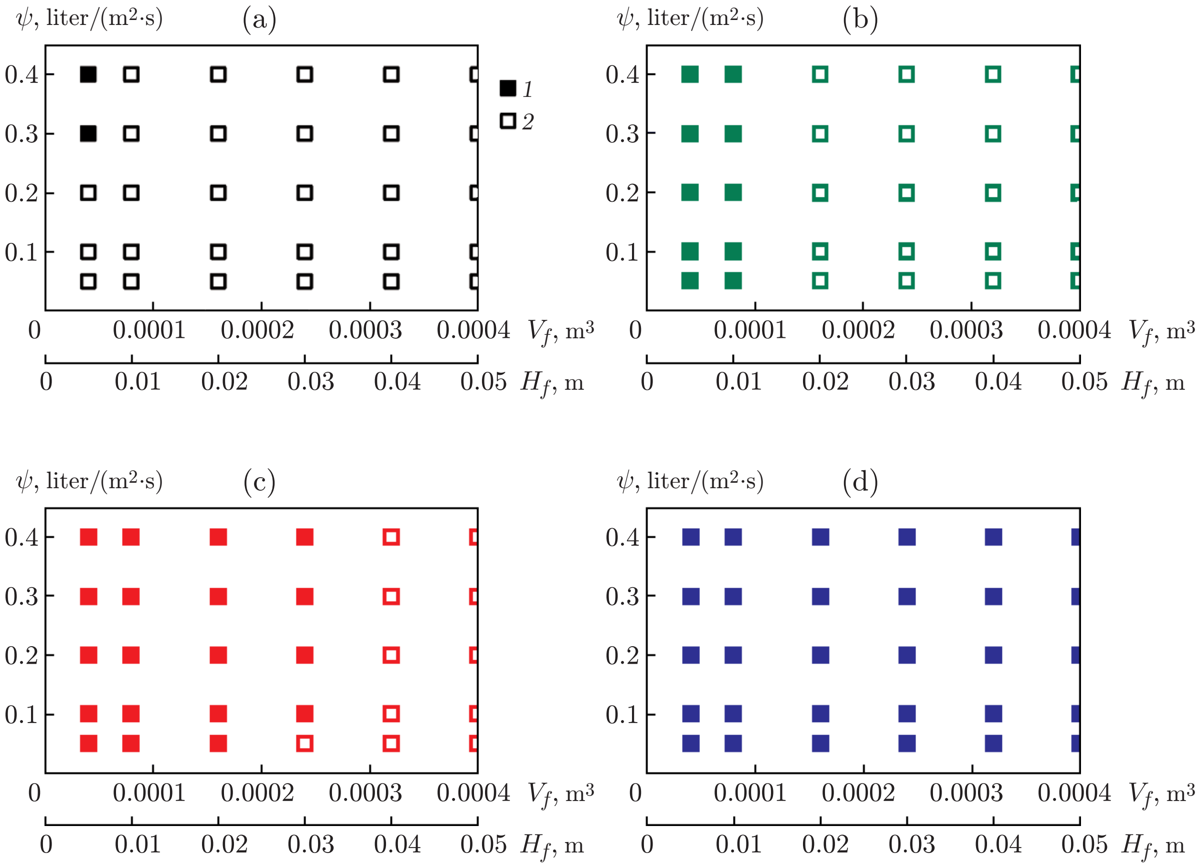

Fig. 7. Dependences of the discharge intensity on the volume and width of a thermally decomposing forest fuel sample (pine needles) at $L \approx 0.06$ m, $U \approx 2$ m/s and various absolute discharge densities: $\zeta = 0.40$ (a), 0.45 (b), 0.50 (c), and 0.55 liter/m^2 (d); points *1* refer to the containment and suppression of flaming combustion and pyrolysis and points *2* refer to the propagation of the combustion front.

Table 2. Predicted minimum values of the water volume and the depth and width of the fire break for containment of combustion of typical forest fuels

Type of forest fuel	Volume of forest fuel sample ahead of fire break, m^3	Area of forest fuel surface ahead of fire break, m^2	Minimum water volume in fire break, liter	Minimum width of fire break, m	Minimum depth of fire break, m
Needles	0.035	0.5	0.125	0.30	0.050
	0.070	1.0	0.250	0.45	0.040
	0.280	4.0	0.380	0.65	0.025
	0.700	10.0	0.675	0.70	0.023
Leaves	0.035	0.5	0.115	0.35	0.020
	0.070	1.0	0.190	0.40	0.018
	0.280	4.0	0.325	0.45	0.016
	0.700	10.0	0.430	0.50	0.015
Mixture of forest fuels	0.035	0.5	0.240	0.40	0.035
	0.070	1.0	0.275	0.60	0.033
	0.280	4.0	0.410	0.70	0.031
	0.700	10.0	0.750	0.75	0.030

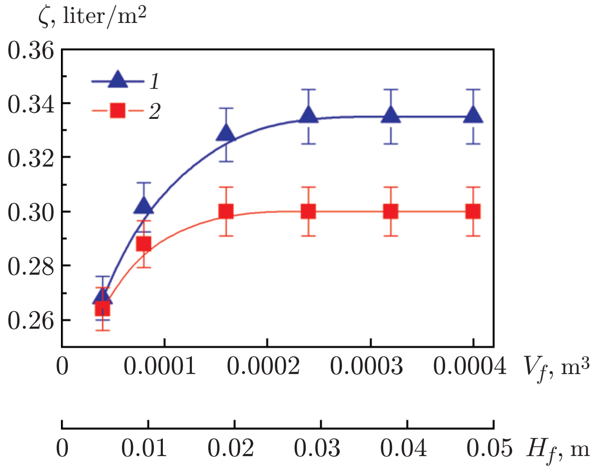

Fig. 8.

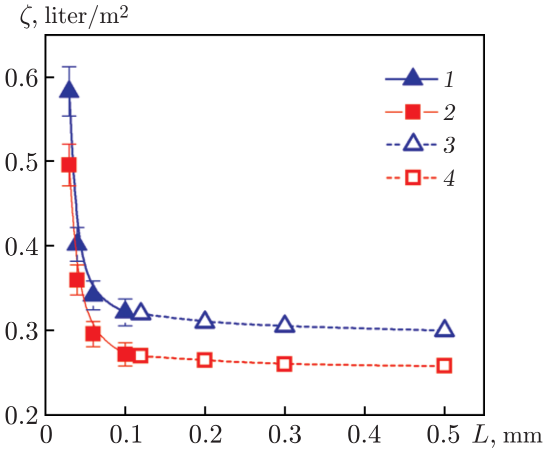

Fig. 9.

Fig. 8. Absolute discharge density versus the volume and width of a thermally decomposing forest fuel ($L \approx 0.06$ m and $U \approx 2$ m/s) for pine needles (*1*) and birch leaves (*2*).

Fig. 9. Absolute discharge density versus the width of the fire break ($U \approx 2$ m/s) for needles (*1* and *3*) and leaves (*2* and *4*); (*1*, *2*) experiment; (*3*, *4*) calculation.

pyrolyzing material, we established the feasibility of containment and suppression of forest fuel pyrolysis in a small area adjacent to the fire break. Therefore, despite the severalfold increase in the volume of pyrolyzing material, the minimum dimensions of the fire break and the discharge density practically do not change (see Fig. 8a).

The necessary and sufficient depths and widths of the fire break for containment and subsequent suppression of flame combustion and thermal decomposition of the investigated forest fuels using a fixed volume of water were obtained by extrapolating the experimental data to wider ranges of L and H (Table 2). In the predictions, it was assumed that the length of the fire break in the form of a wet layer of forest fuel was equal to the transverse size of the thermal decomposition front of the material and that the effective discharge density (specific consumption) was chosen taking into account the results obtained in the experiments (see Figs. 7 and 8).

From Table 2 it follows that effective containment of combustion of common types of forest fuels is provided with small water volumes and fire-break sizes. It is required to perform field tests at specialized test sites of the

Russian Emergencies Ministry to verify the main parameters (see Table 2) of the fire break for containment of forest fuel combustion. The results of the study and the data of [24–36] can be used to predict conditions for containment of flaming combustion and pyrolysis of a large group of forest fuels for fire areas of various sizes.

CONCLUSIONS

1. The results of the experiments using three modes of spraying water ahead of the combustion front and in the front of the ground forest fire model lead to the following conclusions. The most rational mode in terms of water consumption and the time for suppressing combustion is spraying water along the boundary of the fire area. From the analysis of fire containment and the volume of usefully consumed (evaporated) water, it follows that the depth H and width L of the fire break have the most significant effect on the deceleration of the combustion front up to the complete cessation of its advance. In the system of coordinates $H(L)$, the regions corresponding to the efficient containment and subsequent suppression of forest fuel combustion were determined.

2. The structure of forest fuel determines the efficiency of using a particular mode of water supply to the combustion zone. This is due to the significant difference between the integral characteristics of the processes of water motion through the layers of needles, leaves, and the their mixture. Containment of flaming combustion of different types of forest fuels is almost equally efficient, and thermal decomposition processes have significant differences.

3. Wind speed determines the speed of motion of the forest fuel combustion front. In the experiments performed, this parameter was varied in the range values possible under laboratory conditions. In practice, wind speeds may be higher. A necessary experimental base has been developed to predict conditions for forest fire containment.

This work was supported by the Russian Science Foundation (Grant No. 18-19-00056).

REFERENCES

1. G. A. Dorrer, *Mathematical Models of the Dynamics of Forest Fires* (Lesn. Prom., Moscow, 1979) [in Russian].
2. A. M. Grishin, *Mathematical Models of Forest Fires* (Izd. Tom. Gos. Univ., Tomsk, 1981) [in Russian].
3. N. V. Baranovskii and G. V. Kuznetsov, *Prediction of Forest Fires and Their Environmental Consequences* (Izd. Sib. Otd. Ross. Akad. Nauk, Novosibirsk, 2009) [in Russian].
4. V. E. Khodakov and M. V. Zharikova, *Forest Fires: Research Methods* (Grin' D. S., Kherson, 2011) [in Russian].
5. O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, *Evaporation and Transformation of Droplets and Large Volumes of Liquid Moving through High-Temperature Gases* (Izd. Sib. Otd. Ross. Akad. Nauk, Novosibirsk, 2016) [in Russian].
6. A. M. Grishin and O. V. Shipulina, "Mathematical Model for Spread of Crown Fires in Homogeneous Forests and Along Openings," Combust., Expl., Shock Waves **38** (6), 622–632 (2002).
7. O. P. Korobeinichev, A. G. Shmakov, A. A. Chernov, et al., "Fire Suppression by Aerosols of Aqueous Solutions of Salts," Combust., Expl., Shock Waves **46** (1), 16–20 (2010).
8. P. Reszka, P. Borowiec, T. Steinhaus, and J. L. Torero, "A Methodology for the Estimation of Ignition Delay Times in Forest Fire Modelling," Combust. Flame **159**, 3652–3657 (2012).
9. R. S. Volkov, A. O. Zhdanova, G. V. Kuznetsov, and P. A. Strizhak, "Suppression of Thermal Decomposition of Forest Fuels in Large Burning Areas," Inzh.-Fiz. Zh. **91** (2), 1–9 (2018).
10. O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, "Experimental Investigation of Atomized Water Droplet Initial Parameters Influence on Evaporation Intensity in Flaming Combustion," Fire Safety. J. **70**, 61–70 (2014).
11. D. E. Calkin, C. S. Stonesifer, M. P. Thompson, and C. W. McHugh, "Large Airtanker use and Outcomes in Suppressing Wildland Fires in the United States," Int. J. Wildland Fire **23** (2), 259–271 (2014).
12. P. A. Strizhak, "Influence of Droplet Distribution in a "Water Slug" on the Temperature and Concentration of Combustion Products in its Wake," J. Eng. Phys. Thermophys. **86** (4), 895–904 (2013).

13. G. V. Kuznetsov and P. A. Strizhak, “Heat and Mass Transfer in Quenching the Reaction of Thermal Decomposition of a Forest Combustible Material with a Group of Water Droplets,” J. Eng. Phys. Thermophys. **87** (3), 608–617 (2014).
14. A. O. Zhdanova, G. V. Kuznetsov, and P. A. Strizhak, “Numerical Investigation of Physicochemical Processes Occurring during Water Evaporation in the Surface Layer Pores of a Forest Combustible Material,” J. Eng. Phys. Thermophys. **87** (4), 773–781 (2014).
15. O. P. Korobeinichev, A. G. Shmakov, V. M. Shvartsberg, et al. “Fire Suppression by Low-Volatile Chemically Active Fire Suppressants Using Aerosol Technology,” Fire Safety J. **51**, 102–109 (2012).
16. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, “The Influence of Initial Sizes and Velocities of Water Droplets on Transfer Characteristics at High-Temperature Gas Flow,” Int. J. Heat Mass Transfer **79**, 838–845 (2014).
17. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, “Experimental Investigation of Mixtures and Foreign Inclusions in Water Droplets Influence on Integral Characteristics of their Evaporation during Motion through High-Temperature Gas Area,” Int. J. Thermal Sci. **88**, 193–200 (2015).
18. O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, “Evaporation of Water Droplets in a High-Temperature Gaseous Medium,” J. Eng. Phys. Thermophys. **89** (1), 141–151 (2016).
19. R. S. Volkov, G. V. Kuznetsov, J. C. Legros,and P. A. Strizhak, “Experimental Investigation of Consecutive Water Droplets Falling down through High-Temperature Gas Zone,” Int. J. Heat Mass Transfer **95**, 184–197 (2016).
20. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, “Experimental Study of the Suppression of Flaming Combustion and Thermal Decomposition of Model Ground and Crown Forest Fires,” Fiz. Goreniya Vzryva **53** (6), 67–78 (2017) [Combust., Expl., Shock Waves **53** (6), 678–688 (2017)].
21. N. A. Loshchilova and I. V. Belyaev, “The Efficiency of Extinguishing Forest Fires by Combining Natural and Artificial Barriers,” Fund. Prikl. Issl. Sovr. Mire, No. 12-3, 31–32 (2015).
22. A. M. Eritsov and V. G. Gusev, “Improving the Technologies of Producing Fire and Control Lines in Forest Fire Extinguishing in Forestry Zones,” Vestn. Povolzh. Gos. Tekh. Univ., Ser. Lesn. Ekol. Prirodopolz., No. 1, 42–56 (2016).
23. N. P. Kopylov, I. R. Khasanov, A. E. Kuznetsov, et al., “Parameters of Water Discharge from the Aircaft in Extinguishing Forest Fires,” Pozhar. Bezopas., No. 2, 49–55 (2015).
24. C. H. Lautenberger and C. A. Fernando-Pello, “A Model for the Oxidative Pyrolysis of Wood,” Combust. Flame **156**, 1503–1513 (2009).
25. R. Sawyer, R. Bradstock, M. Bedward, and R. J. Morrison, “Fire Intensity Drives Post-Fire Temporal Pattern of Soil Carbon Accumulation in Australian Fire-Prone Forests,” Sci. Total Environ. **610/611**, 1113–1124 (2018).
26. I. S. Voitkov, R. S. Volkov, A. O. Zhdanova, et al., “Physicochemical Processes in the Interaction of Aerosol with the Combustion Front of Forest Fuel Materials,” Prikl. Mekh. Tekh. Fiz. **59** (5), 143–155 (2018) [J. Appl. Mech. Tech. Phys. **59** (5), 891–902 (2018)].
27. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, “Motion of Water Droplets in a Forest Fuel Layer in the Course of its Thermal Decomposition,” Thermal Sci. **22** (1), 301–312 (2018).
28. O. P. Korobeinichev, A. A. Paletsky, M. B. Gonchikzhapov, et al., “Combustion Chemistry and Decomposition Kinetics of Forest Fuels,” Procedia Eng. **62**, 182–193 (2013).
29. A. A. Paletsky, M. B. Gonchikzhapov, and O. P. Korobeinichev, “Molecular Beam Mass Spectrometric Study of the Pyrolysis of Forest Fuels,” Sibbezopasnost’-Spassib., No. 1, 97–98 (2011).
30. M. B. Gonchikzhapov, A. A. Paletsky, and O. P. Korobeinichev, “Pyrolysis Kinetics of Forest Fuels in an Inert/Oxidizing Medium at Fast and Slow Heating Rates,” Sibbezopasnost’-Spassib, No. 1, 38–44 (2012).
31. R. Wadhwani, D. Sutherland, K. A. M. Moinuddin, and P. Joseph, “Kinetics of Pyrolysis of Litter Materials from Pine and Eucalyptus Forests,” J. Thermal Anal. Calorimetry **130**, 2035–2046 (2017).
32. E. A. Moskvilin, “The Use of Aviation to Extinguish Forest Fires,” Pozhar. Bezopasnost’, No. 1, 89–92 (2009).
33. A. M. Grishin and A. I. Filkov, “A Deterministic-Probabilistic System for Predicting Forest Fire Hazard,” Fire Safety J. **46** (1/2), 56–62 (2011).
34. N. V. Mikhailova and H. D. Gutsev, “Results of Laboratory Studies of the Properties of New Fire Extinguishing Compositions for Fighting Forest Fires,” Bezopasnost’ Zhiznedeyat., No. 4, 33–39 (2014).
35. W. J. Parker, R. J. Jenkins, C. P. Butler, and G. L. Abbott, “Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity,” J. Appl. Phys. **32**, 1679–1684 (1961).
36. A. Duane, M. Piqué, M. Castellnou, and L. Brotons, “Predictive Modelling of Fire Occurrences from Different Fire Spread Patterns in Mediterranean Landscapes,” Int. J. Wildland Fire **24**, 407–418 (2015).