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Experimental Study of Regularities in Suppression of Flame Combustion and Thermal Decomposition of Forest Combustible Materials Using Aerosols of Different Dispersiveness

A. O. Zhdanova[*], **G. V. Kuznetsov**[**], **and P. A. Strizhak**[***]

National Research Tomsk Polytechnic University, pr. Lenina 30, Tomsk, 634050 Russia

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Abstract—This paper presents results of experimental studies on the heat and mass transfer and phase transformations in suppression of thermal decomposition and flame combustion of a group of typical forest combustible materials (leaves and needles used as examples) due application of water aerosol and a group of droplets of a fixed total volume. The main attention is paid to the experimentally found effect of aerosol dispersiveness (via variation in the concentration and size of droplets) on the integral characteristics of the heat and mass transfer processes and phase transformations. The effective irrigation density, the minimum (necessary and sufficient) volume, and the respective specific water consumption for complete termination of destruction of forest combustible materials are calculated. Three most typical schemes of sprayed liquid interaction with the surface of forest combustible material under intensive pyrolysis are considered with the aim of establishing conditions for inhibition, localization, and complete cessation of the process of destruction of forest combustible materials. Dependencies illustrating how the properties and structure of layers of forest combustible materials affect the characteristics of these processes are established.

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1. INTRODUCTION

The problem of monitoring and forecasting the main characteristics of the processes of flame combustion and thermal decomposition of typical forest combustible materials has remained relevant for many years due to the ongoing attempts to create effective technologies to prevent and localize spread of forest fires [1–6]. These natural disasters cause enormous material damage and are a real danger to the population in many forest-covered regions of the world [7–10]. Unfortunately, no standardized effective technologies for extinguishing large forest (ground, crown, and mixed, or combined) and steppe fires with due account of the effect of at least a group of major significant factors and conditions have been developed so far. Such are conclusions by specialists at the highest level (at international fire safety congresses, for example, in the USA, Canada, Australia, Europe, and Asia in 2010–2018) [11–15]. Currently, the most common method of extinguishing large forest fires is discharging water locally into the combustion zone, with involvement of aviation (airplanes, helicopters, unmanned aerial vehicles, etc.) [16–18]. Such an approach can hardly be taken as a technique of extinguishing large fires since the conditions for complete cessation of the process of burning and destruction, as a rule, are not achieved [13–15]. In the most favorable conditions, the propagation of the flame combustion and thermal decomposition fronts can be slowed down for a short time [11–13]. The main problem is that the typical aircraft most often use sluice discharge systems, which does not allow spraying water or rationally dosing it [11, 12]. It is advisable to use model fire hotbeds to study the fundamental differences between the conditions and characteristics of suppression of flame combustion and thermal decomposition of the most typical forest combustible materials [19–23] using aerosols of different dispersiveness, as well as

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[*] E-mail: `zhdanovaao@tpu.ru`
[**] E-mail: `kuznetsovgv@tpu.ru`
[***] E-mail: `pavelspa@tpu.ru`

non-sprayed bulks of water. In so doing, it is important to take into account schemes of liquid injection into the pyrolysis zone that are widely used for blocking, localizing, and suppressing combustion sources. The main schemes have been examined in laboratory experiments and field trials [24–26].

The purpose of this work is to experimentally determine the effective conditions for blocking, localizing, and completely stopping the process of destruction of forest combustible materials (FCMs) using a limited amount of water and varying the aerosol dispersiveness and the schemes of water supply to the thermal decomposition zone and before it.

2. EXPERIMENTAL STAND AND RESEARCH METHODS

The experiments included *two stages*. The *first* one involved recording the conditions and characteristics of the processes of thermal decomposition and flame combustion of FCMs at series delivery of a group of large water droplets, as well as one-time inflow of the total bulk of the latter, to the combustion zone. Similar studies were carried out with a pulsed aerosol feed and a one-time (i.e., continuous) injection of water volume identical to that in the first case. At the *second* stage, experiments were carried out with the aim of studying the effect of droplet aerosol parameters on the characteristics of the inhibition of flame combustion and thermal decomposition of FCMs.

2.1. Materials

The studies were carried out with a group of typical forest combustible materials: birch leaves and pine needles. The relative humidity of the FCMs was determined by the formula $\gamma_f = (m_{fw} - m_{fd})/m_{fw} \cdot 100$, %. In additional experiments, the following γ_f values were established: 5–8% for birch leaves and 7–10% for pine and spruce needles.

At the *first stage*, a weighed sample of material was placed in a small cuvette in the form of an elongated cylinder. The combustion suppression was carried out using series supply of droplets along the axis of symmetry of the cuvette (Fig. 1b). The dimensions of the latter were chosen similarly to experiments [24–26] in accordance with the limitations of the experimental test facility and specific heat generation in the combustion zone: the height (it corresponded to the thickness of the weighed sample of the material) and diameter were 100 mm.

At the *second stage*, the model fire hotbed was a metal tray with the following dimensions (similarly to experiments [24]) (Fig. 1b): length of 310 mm, width of 195 mm, and depth of 45 mm.

2.2. Generation of Droplets and Aerosols

The *first stage* of the experiments involved series supply of a group of water droplets and one-time injection of the total volume of water along the axis of symmetry of the sample. At the *first* and *second stages*, the aerosol was applied using a group of nozzles with different dispersiveness (from 0.05 mm to 0.25 mm), density, and intensity of irrigation. The main attention is paid to the study of the effect of the scheme of water spraying in the front of combustion of the material and before it. Similarly to experiments [24–26], three schemes of water spraying were used (with a fixed width of the barrage $L_a = 50$ mm and air velocity $U_a = 2$ m/s): 1—in front of the combustion front, 2—in the combustion front, and 3—combined scheme with spraying water before the burning front and in it. Figure 1 shows the scheme of the stand with illustration of the two stages and the different spray patterns used.

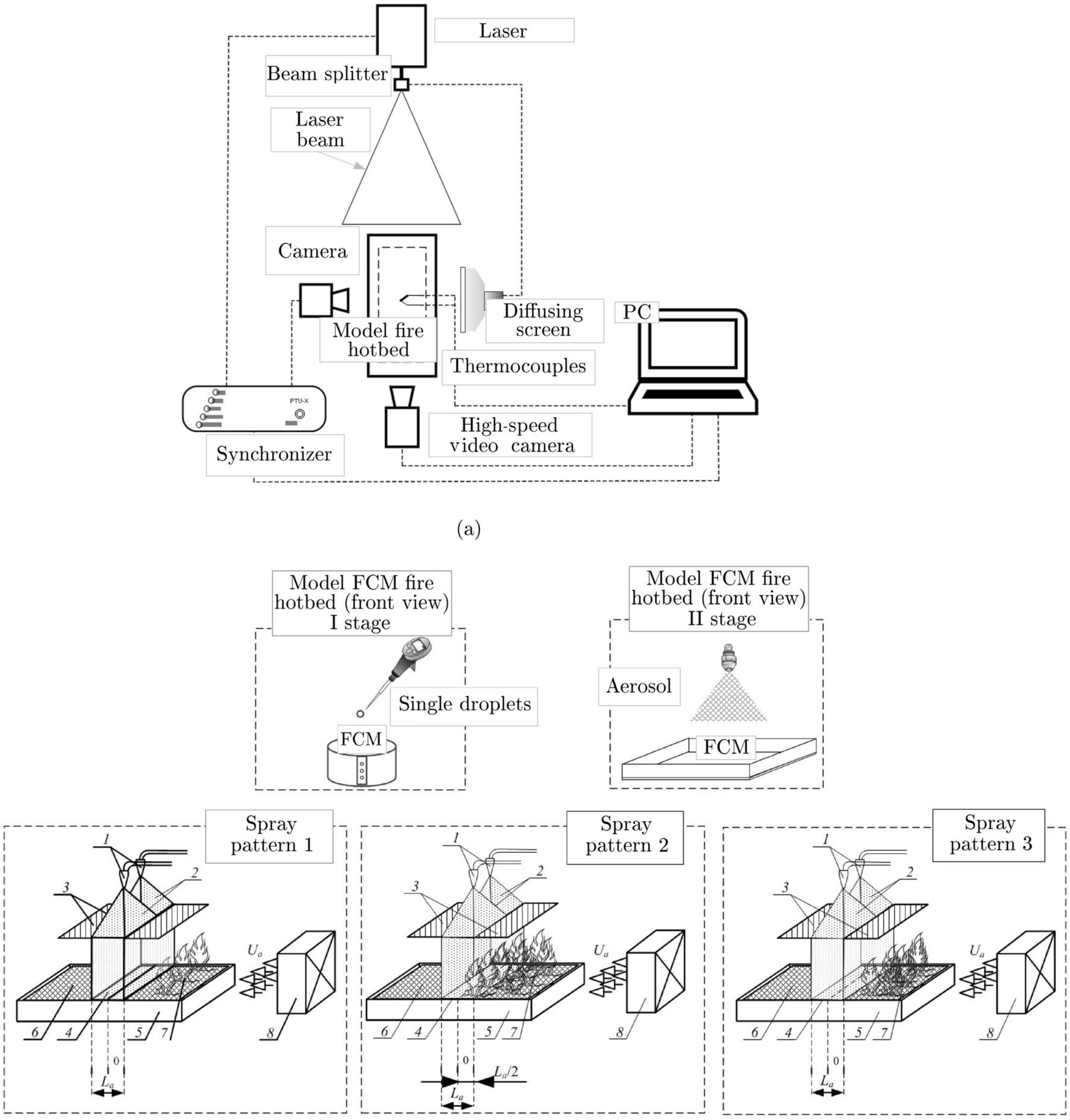
2.3. Recorded Characteristics and Errors

During the experiments, the following parameters were recorded:

—the time for suppression of flame burning (according to a stopwatch and visual monitoring of flame extinction), thermal decomposition of the material (from the material layer temperature lowering below the value of beginning of thermal decomposition (a threshold value of 80° C was assumed for all materials); platinum rhodium-platinum needle-shaped thermocouples were placed in the thickness of sample (temperature range: −50–1500° C, systematic error of measurement: 1.5 K, time of thermal lag: 0.1 s);

—the amount of water used, known from the values of specific consumption and the time of liquid delivery;

—the droplet size when using optical registration methods (Shadow Photography and Interferometry Particle Imagine as in [27–30]).



(a)

(b)

Fig. 1. Scheme of (a) experimental stand and (b) model fire hotbeds at first and second stages: 1—nozzles, 2—water aerosol, 3—water tanks, 4—droplet flow, 5—metal tray, 6—FCM, 7—flame, 8—air blower.

3. RESULTS AND DISCUSSION

3.1. Main Regularities of Investigated Processes of Combustion Suppression

The experiments have shown that effective suppression of flame combustion and thermal decomposition of studied typical forest combustible materials is possible with simultaneous effect of a group of factors and intensification of respective processes. In particular, the following decisive factors can be singled out: smothering of the combustion zone due to water vapor; decrease in the temperature in the combustion zone due to convective cooling with water (heat spent for heating the water) and energy-consuming (due to a high heat of vaporization of 2.26 MJ/kg) endothermic phase transformations; slowing down of exothermic physicochemical transformations because of intense diffusion of water vapor, leading to decrease in the concentrations of combustible products of pyrolysis and oxidant in the combustion zone. Unfortunately, current fire extinguishing technologies are based on intensifying one (rarely two or three simultaneously) known mechanisms in each specific case [11–18]. As a result, it is difficult to consider any of the modern technologies as fully effective.

In this work, the main attention is paid to studying the possibility of intensifying the process of suppressing combustion of typical FCMs due to the above three mechanisms of localization and prevention of pyrolysis of materials. In particular, clauses 3.2–3.5 present ways of studying the mechanisms and methods to optimize the processes of supplying water droplets to the zone of flame combustion and pyrolysis, their passage through layers of the material, retention in the layers, and evaporation. The optimal parameters for spraying water into the zone of flame combustion and pyrolysis of FCMs have been determined, as well as the relationship between these parameters, with due account of specific structure of material and a sample as a whole.

3.2. Comparison of Conditions of Combustion Localization with One-Time or Distributed Supply of Droplets and Aerosol

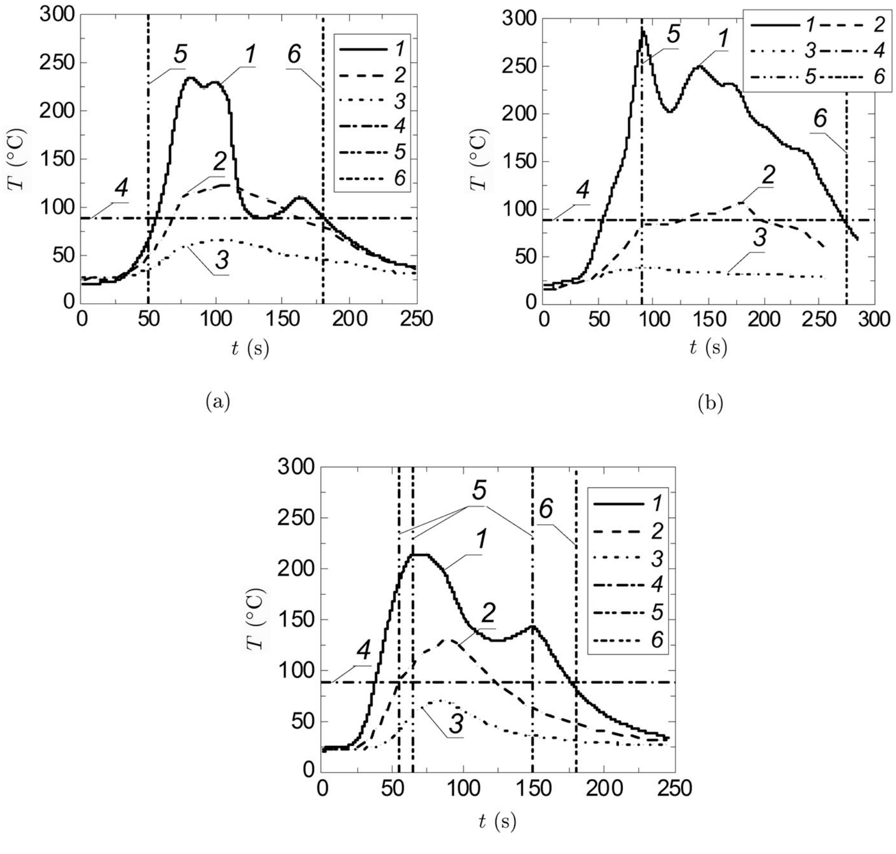
Figure 2 shows typical trends of temperature changes in reacting layers of FCMs at series delivery of large droplets of water, as well as aerosol with dosing and continuous spraying of liquid into the combustion zone. One can see clearly specific differences in the maximum temperature values in deep layers of the material, as well as in the times and rates of change in this temperature, at different methods of water delivery to the combustion zone. With series supply of droplets, the suppression of combustion occurs significantly faster (2–3 fold) than with the use of aerosol. However, the volume of water used almost 5 times exceeds the volume at application of aerosol. With the use of pulsed schemes of liquid delivery, the time for suppressing combustion increases, but the volume of water decreases several fold. In this case, dosing of water delivery inhibits significant reduction of the temperature in the deep layers. The main effect shows in the near-surface layers, which are soaked with water quite quickly, even at dosed water application. In particular, in all experiments, the values of temperature on the first and second thermocouples (located in the subsurface layer and in the middle part of the sample) decreased rapidly in all cases. In general, we have revealed trends, which show unnecessity of excessive increase in the volume of water delivered to zones of flame combustion and pyrolysis of material. As a consequence, it is important to determine the main directions of optimization of water use and justify those using experimental data.

Figures 3 and 4 show the results of experiments on registering two main characteristics (volume of water spent and time for suppression of combustion) of the investigated processes with the use of the most typical schemes for water delivery to the combustion zone: one-time injection of the entire volume or organization of series aerosol spraying. Figure 3 shows the dependences for a group of successive droplets, and Fig. 4 presents values from the experiments with aerosol.

From the results of the experiments presented in Fig. 3, one can conclude that series delivery of water droplets to the combustion zone does not significantly optimize the liquid consumption. The amount of water spent is almost the same as at one-time application of the liquid, whereas the localization time increases significantly at series delivery of droplets. This is due to the fact that at one-time application of water to the combustion zone, the liquid pressure forces compact virtually all layers of the material and block the pores, through which the pyrolysis products turn to the gas phase and intensify the flame combustion (such conclusions can be made from video frames recorded with a high-speed video camera). In case of series delivery of droplets, the combustion localization processes proceeded slowly because of the significantly smaller droplet sizes as compared with the transverse dimensions of sample.

A different trend has been established at aerosol application. In particular, Fig. 4 shows that serial (pulsed) delivery of droplet aerosol facilitates more rational water consumption when the samples are small (thin). This is due to the fact that under such conditions the flame combustion and thermal decomposition can be suppressed with a sufficiently small volume of water and its penetration only into the surface layers of the sample. At large thicknesses of material, the results of the experiments are in good agreement with similar data with serially delivered droplets (Fig. 3).

It should be noted that the high-speed video recording made it possible to identify fundamental differences in the conditions of propagation of the fronts of flame combustion and pyrolysis in experiments with needles and leaves. These features have a significant effect on the characteristics of the combustion suppression processes, in particular, on the extinction times and volumes of water used. For example, in Fig. 4, one can see that the water delivery conditions had a minor effect on the suppression of the



(a)

(b)

(c)

Fig. 2. Temperature trends in extinguishing combustion and thermal decomposition of pine needles (sample thickness $h_f = 50$ mm and diameter $d_f = 25$ mm): (a) supply of single droplets (n = 9, $V_d = 50$ μl, $V_{e\Sigma} = 450$ μl); (b) one-time delivery of water aerosol (n = 1, $t_{n1} = 3$ s, $Ve_\Sigma = 100$ μl); (c) pulsed delivery of aerosol (n = 3, $t_{n1} = 2$ s, $Ve_\Sigma = 200$ μl); *1*—first thermocouple; *2*—second thermocouple; *3*—third thermocouple; *4*—temperature of beginning of thermal decomposition of FCM; *5*—beginning of generation of water droplets and aerosol; *6*—time of localization of combustion and thermal decomposition of FCM.

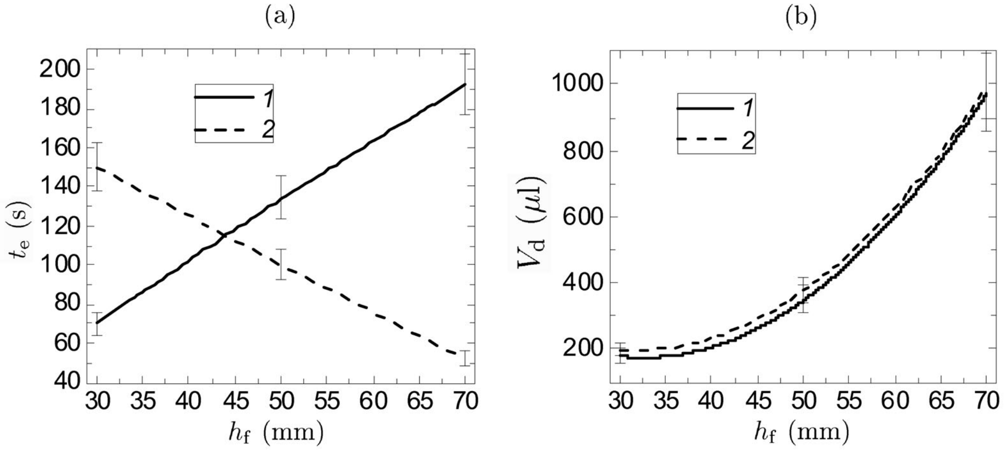


Fig. 3. (a) Time for suppression of combustion and (b) water volume applied versus thickness of material under pyrolysis conditions with fire hotbeds exposed to single droplets (*1*) and after one-time delivery (*2*) of fixed volume of liquid.

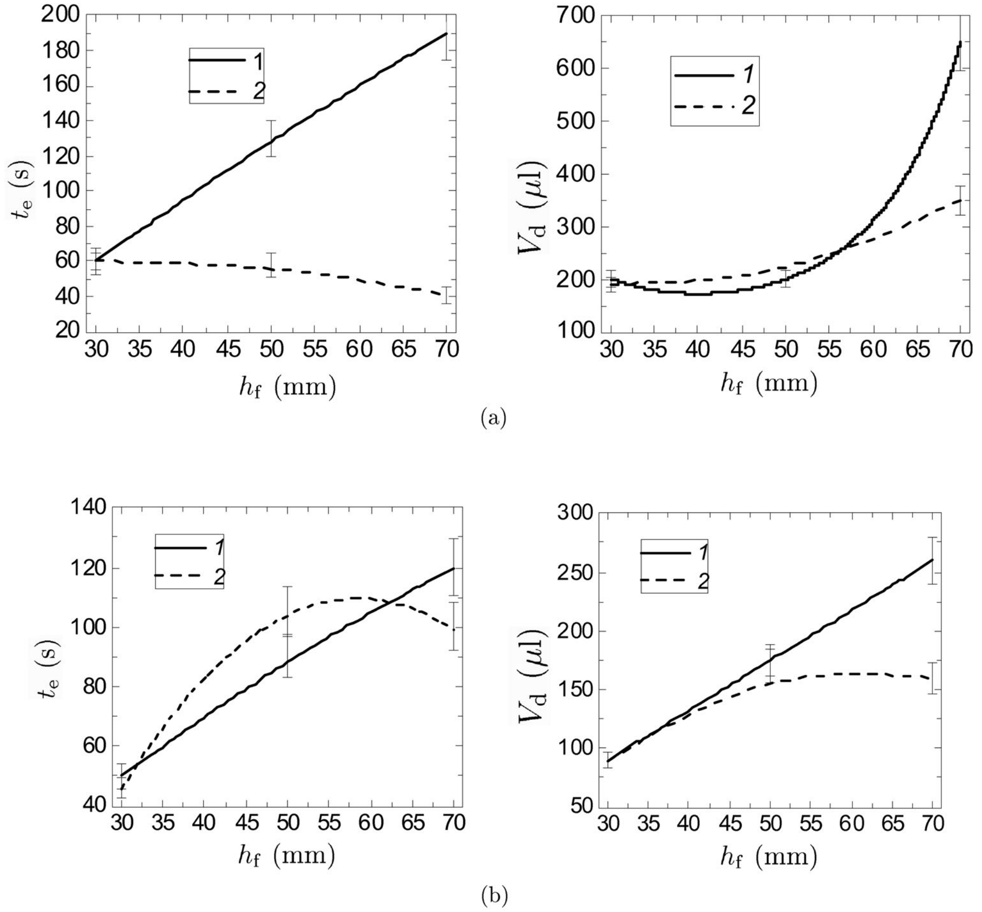


Fig. 4. Time for suppression of combustion and water volume applied versus thickness of material under pyrolysis, (*1*) fire hotbed exposed to pulsed aerosol and (*2*) after a one-time delivery of fixed volume of liquid: (a) pine needles, (b) birch leaves.

pyrolysis of the leaves. The reason is that the front of the pyrolysis of the leaves spreads extremely slowly into the depth of the sample. The main heat generation and formation of products of thermal decomposition occur in the surface layers. Large fraction of water is inhibited when moving in the surface layers of the sample due to the high sample density. Therefore, the suppression of the flame burning and pyrolysis of the leaves occurs fairly quickly (several times faster than in experiments with needles).

Analysis of conditions for suppression of thermal decomposition of needles has revealed a different trend. The front of pyrolysis was spreading intensively into the deeper layers of the sample, and the water was also penetrating to a great depth. Therefore, the volume of the liquid applied and the conditions of its delivery turned out to be decisive factors. The larger was the one-time volume, the deeper passed the liquid, suppressing the thermal decomposition of the material throughout its thickness.

3.3. Dispersiveness of Aerosol

Experiments to determine the aerosol droplet size ranges that reduce the times for localization of combustion of materials and the volumes of liquid spent were of greatest interest. Specialized nozzles varied the respective (average) radii of droplets in the aerosol with monitoring by means of optical methods and cross-correlation software and hardware complex (similarly to the known methods [27–30] based on the use of contactless optical recording methods). Figure 5 shows typical images of aerosol droplets, obtained with high-speed video recording.

Figure 6 presents the times for localization of FCM combustion (by the example of needles since namely in the experiments with needles the influence of the injection conditions was the most noticeable) versus the average size of aerosol droplets for the three schemes of spraying water into the combustion zone. The volumes of unevaporated water that passed through all layers of the sample are also given. In the first approximation, such volume can be considered excessive or inefficient, but in fact even small amounts of water contribute to substantial cooling of deep layers of FCMs due to the high heat capacity of the liquid. Information on unevaporated volumes of water is needed for analysis of the dominant physical processes in the layers of the material.

Quite expectedly, the larger was the droplet size, the shorter were the times for localization of flame combustion of the material and suppression of pyrolysis throughout the depth. Moreover, the shortest times for combustion suppression were in experiments with the second spraying scheme, with uniform supply of water over the entire free surface of the FCM. With other spraying schemes, longer durations of combustion suppression were recorded. However, it is important to note that the times for localization of combustion depend on the size of aerosol droplets only in a limited range. So, for example, the R_d range in Fig. 6 can be divided into two sections: up to 0.12 mm and above this value. In the second section, the times for flame combustion suppression practically did not change with the growth of droplet sizes, and the pyrolysis duration decreased by less than 10%. In the first section, the influence of R_d is more substantial.

If one compares the volumes of unevaporated water for the spraying schemes, then the established dependences are quite obvious. The substantially nonlinear dependence of the investigated water volume on the droplet sizes for the first scheme is quite anticipated; for the second and third ones, the growth is fairly moderate and almost identical. The range of droplet sizes up to 0.12 mm should be noted, in

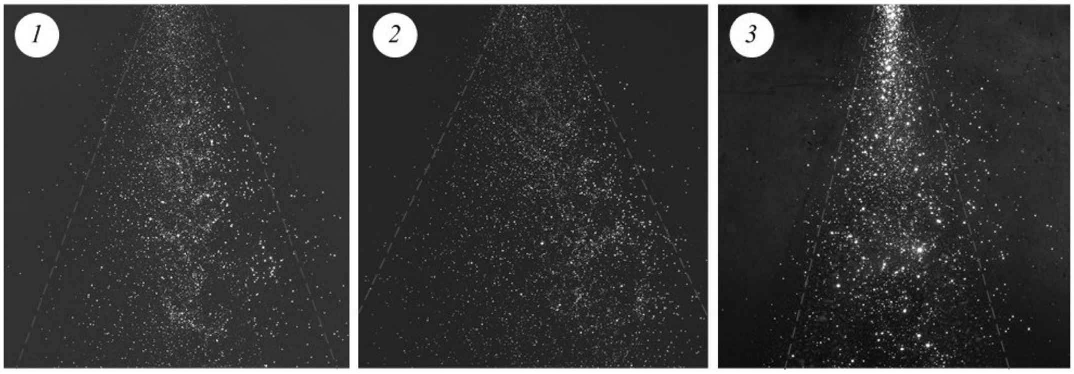
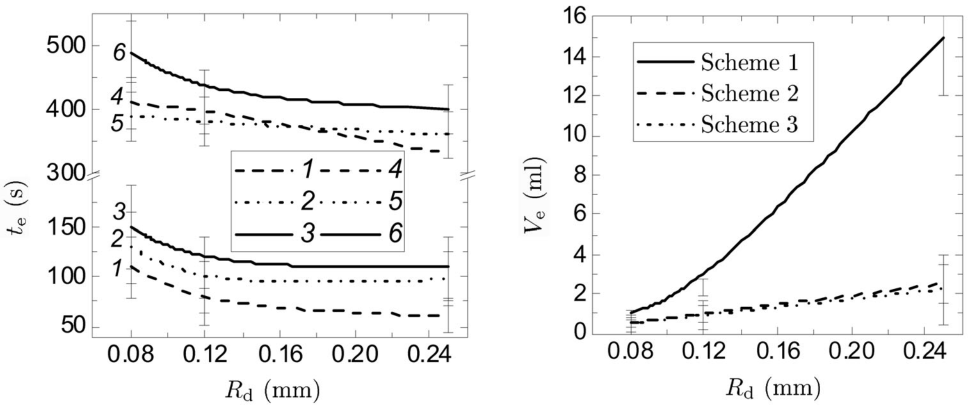
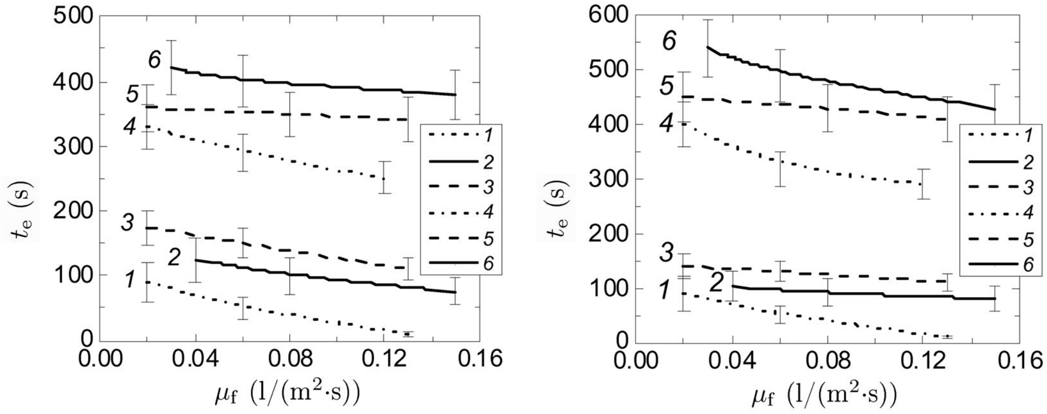


Fig. 5. Typical videograms of experiments with registration of sizes of droplets in aerosol: *1*—$R_d = 0.08$ mm; *2*—$R_d = 0.12$ mm; *3*—$R_d = 0.25$ mm.



(a) (b)

Fig. 6. Times for suppression of flame burning of FCMs (*1*–*3*) and thermal decomposition (*4*–*6*) (needles) using (a) droplet aerosol of different dispersion and unevaporated volume of water; (b): *3*, *6*—scheme 1; *1*, *4*—scheme 2; *2*, *5*—scheme 3.



(a) (b)

Fig. 7. Times for suppression of flame and heterogeneous combustion of FGM at varying irrigation intensity: (a) needles, (b) leaves; *1–3*—flame combustion; *4–6*—thermal decomposition; *1*: $R_d = 0.08$ mm; *2*: $R_d = 0.12$ mm; *3*: R_d =0.25 mm; *4*: $R_d = 0.08$ mm; *5*: $R_d = 0.25$ mm; *6*: $R_d = 0.12$ mm.

which almost the entire volume of water evaporated in the material layers in all the spraying schemes considered (the differences between the curves are minimal and generally correspond to the confidence intervals of the experimental values).

In the real practice of inhibition of burning of various materials (not only forest elements), the main parameter of liquid spraying is the irrigation intensity (the terms “irrigation density” or “specific consumption” are often used). Figure 7 shows the experimental times for suppression of flame combustion and pyrolysis of material versus the irrigation intensity. Analysis of the experimental data makes suggests that the established dependencies are nonlinear, which may be due to the significant differences in the rates of propagation of droplets through the layers of the material and, as a consequence, the respective dependences of the water evaporation rates on the surface temperature. As was expected, increase in the irrigation density can reduce the times for combustion localization several fold.

3.4. Density of Samples of Forest Combustible Materials

Figure 8 shows typical dependences illustrating the fundamental differences in the nature of the movement of water droplets through layers of needles or leaves. It can be seen that the water droplets move quite quickly through layers of needles and settle in the deeper layers. In experiments [24–26], using low-inertia thermocouples it was found that these velocities can increase by several times in intensive pyrolysis of needles since large cavities are formed in the deeper layers. In experiments with leaves, the main volume of water injected is retained in the surface layers of the material. As a consequence, the depths of soaking (a group of terms can be used, for example, “wetting” or “liquid accumulating in respective layers”) of the FCM are significantly smaller as compared with experiments with needles. Only with a significant increase in the volume of water injected and the duration of its spraying, the sample is soaked through the entire thickness.

The experiments showed the density of the samples of all materials studied to affect significantly the main recorded parameters (for different schemes of water spraying and conditions for water movement). Figure 9 presents the corresponding experimental data, on the basis of which at higher density a steady several-fold increase in the required and sufficient volume of water is singled out, all the averaged dependencies being almost linear. Such results can be explained by the features of the movement of liquid droplets through the layers of the sample. The higher is the sample density, the bigger are the volumes of liquid retained in the surface layers, impeding the penetration of new volumes of water into the sample layers. Only with increase in the latter, the necessary pressure was provided, and they penetrated to a greater depth. In such conditions, the processes of suppression of combustion and pyrolysis were quite long. As a result, the volume of water discharged during these times increased significantly.

Figure 10 presents processed experimental results in the form of the times for FCM combustion suppression versus the volume of water used at different densities of the samples. It is clearly seen that

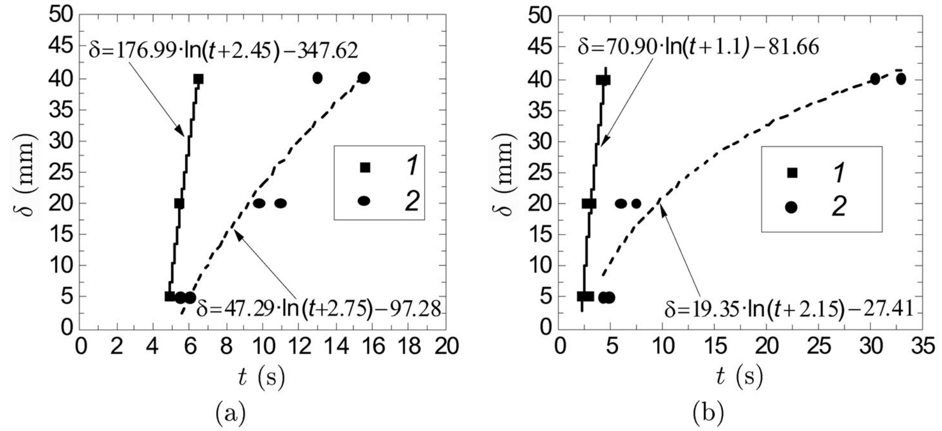


Fig. 8. Depth of water penetration into FCM sample vs. time of spraying at different sizes of droplets in aerosol (average radii are given): (a) $R_d \approx 0.12$ mm, (b) $R_d \approx 0.25$ mm; *1*—needles, *2*—birch leaves.

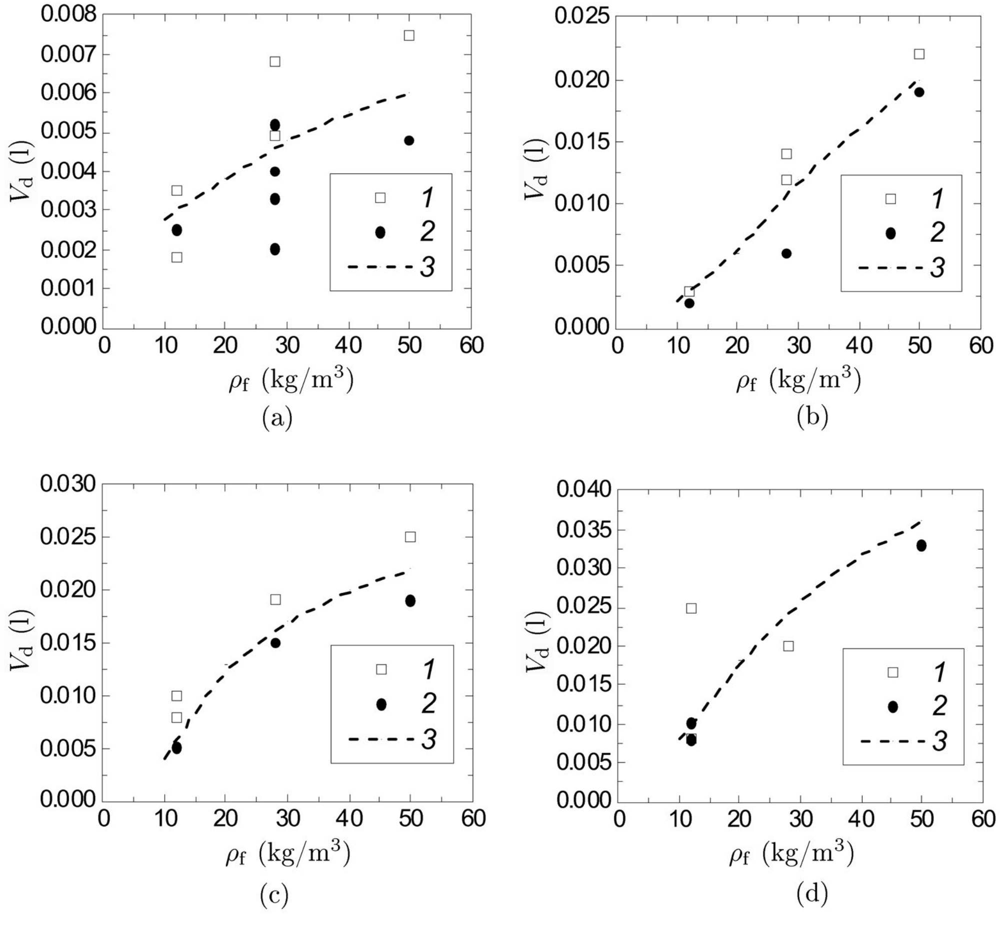


Fig. 9. Volume of water vs. FCM sample density: *1*—fire suppression; *2*—burn-through; *3*—boundary line; (a) and (b) birch leaves under conditions of scheme 1 and 3, respectively; (c) and (d) needles under conditions of scheme 1 and 3, respectively.

the larger is the density of FCM sample, the bigger is the water volume required for terminating both the flame combustion and thermal decomposition of the material. The dependences of the times required for localization of flame combustion and suppression of pyrolysis on the water volume differ in their nature (Fig. 10). In the case of flame combustion, the dependence is weak for the three material densities studied. This result could be foreseen since the flame combustion of the material can be suppressed due to lowering of the gas phase temperature and inhibition of the escape of the pyrolysis products from the material layers because of the appearance of liquid film on the surface of the material. As for suppression of pyrolysis of FCM, increase in the volume of water contributes to noticeable decrease in the thermal decomposition times, i.e., it inhibits this process throughout the depth of the sample. The higher is the sample density, the slower is the movement of water into deeper layers under pyrolysis conditions. Therefore, increase in the sample density leads to growth of the times for localization and complete cessation of thermal decomposition.

The respective slowing of the water penetration into the FCM is not only because of the higher resistance of the medium because of, for example, a larger number of needles per unit mass or volume of the material. In addition, at a higher density of the FCM sample, the area from which the gaseous pyrolysis products enter the pores of the material enlarges. Therefore, the intra-pore pressure of the hot gases and the pressure drop across the thickness of the material go up. Moving to the heating surface, the gaseous products of the pyrolysis of the material inhibit the (counter) movement of droplets through the pores. The higher is the rate of the thermal decomposition of the FCM (and the mass flow rate of the combustible gases resulting from pyrolysis), the slower moves the water under the action of gravity into the deeper layers of the sample.

3.5. The Minimum Required Volume and Optimal Scheme of Liquid Application

Summarization of the results of the research yielded relationships among the main parameters of the processes. In particular, the following dependences were studied: depth of water penetration into FCM layers versus volume of liquid used, volume of liquid applied versus sample thickness and density, and irrigation intensity versus sample density and thickness. It has been established that the integral dependence of the specific irrigation density (or specific consumption) on the volume of material under pyrolysis conditions plays a decisive role.

Figure 11 presents some of the dependences obtained from the results of experiments with needles and leaves. All the established dependences, two of which are presented in Fig. 11, contain two characteristic intervals: in the first one, the influence of the volume of the FCM under pyrolysis conditions is significant, and in the second one, it is almost unnoticeable. So, one can conclude about some necessary saturation (wetting) of material with water, exceeding which would be unnecessary.

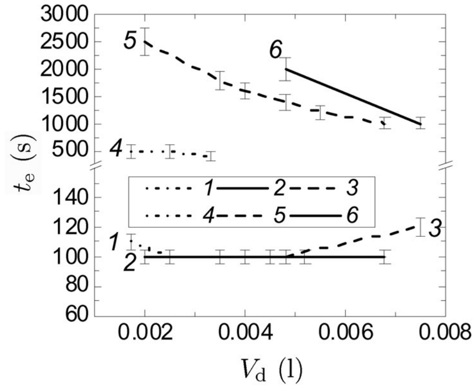


Fig. 10. Time for suppression of flame combustion (*1*–*3*) and thermal decomposition (*4*–*6*) for first scheme and three different values of density of birch leave sample: *1*, *4*: $\rho_f = 13$ kg/m^3; *2*, *5*: $\rho_f = 26$ kg/m; *3*, *6*: $\rho_f = 50$ kg/m^3.

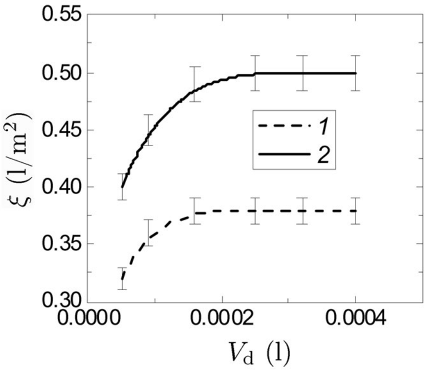


Fig. 11. Necessary and sufficient values of rational density of FCM irrigation (specific consumption) in barrage to ensure localization of flame combustion and pyrolysis of material: *1*—birch leaves; *2*—pine needles.

Because of the large porosity and high rates of pyrolysis, the volumes of water necessary and sufficient to suppress burning of needles are several times higher than in the case of leaves. Experimental data [24–26] enable forecasting differences in experimental results for needles, leaves, and a mixture of the materials (with dominating concentration of one or the other component).

The density of sample exerts a significant effect on the flame combustion and pyrolysis, as well as on their localization and suppression. Therefore, it would be rational to choose parameters for spraying water into the combustion zone with due account of the established scope of influence of this factor.

The videograms of the experiments and the readings of the thermocouples in the layers of samples suggest that a rather large part of the water discharged into the pyrolysis zone stays unevaporated during the process of combustion suppression because of the high heat capacity of water. Its movement through the layers of sample (especially noticeable in experiments with needles) leads to a significant decrease in temperature in the deeper layers. As a result, the rate of vaporization becomes small. However, the process of combustion suppression runs intensely and thus both the high heat of vaporization of the liquid and its heat capacity matters.

Using dependencies in Fig. 11, one can forecast the minimum amounts of water sufficient to suppress combustion of FCMs of different masses. This is the basis for choosing parameters for spraying the liquid in conditions of real ground forest fires.

4. CONCLUSIONS

Analysis of the results of the experiments suggests that effective inhibition of flame combustion and thermal decomposition of typical forest combustible materials requires specialized spraying of water. In the present work, dependences have been obtained that can be used in development of appropriate algorithms of specialized spraying. Significant parameters to take into account are the density, surface structure, and properties of forest combustible materials, water volume applied, characteristics of spray devices, and the time required to suppress the flame combustion and pyrolysis. The results of the experiments presented in the article are a basis for creation of prognostic models and corresponding algorithms for effective interaction of liquids with forest combustible materials under pyrolysis conditions. The main objective is to rationalize the use of the liquid volume.

NOTATIONS

d_f, h_f—diameter and height of cuvette for placement of material (they corresponded to sample diameter and thickness), mm

L_a—barrage width, mm

m_{fw}—mass of FCM before heat drying, kg

m_{fd}—mass of FCM after heat drying, kg

n—number of droplets (injections)

R_d—radius of droplets, mm

t—time, s

t_e—time for localization of FCM sample burning, s

T—temperature, °C

U_a—air flow speed, m/s

V_d—droplet volume, l

$V_{e\Sigma}$—total volume of water discharged, l

V_e—total volume of water remaining in tray (non-evaporated), l

δ—depth of water penetration through layers of sample, m

γ_f—relative humidity of FCM, %

ρ_f—sample density, kg/m^3

μ_f—irrigation intensity, l/(m^2·s)

ζ—irrigation density, l/m^2

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