SUPPRESSING THE THERMAL DECOMPOSITION OF FOREST FUEL USING THE DIFFERENT WATER SPRAYING SCHEMES

by

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This article presents the main findings of the experimental research into the fire suppression by continuous spraying of water over the combustion zone and by pulsed liquid aerosol delivery according to two schemes. The test samples contained either birch leaves only or mixed of (leaves, twigs, and needles). We monitored the temperature in the fuel bed and used thermocouple readings to determine the conditions and characteristics of suppressing the combustion and thermal decomposition of the material. Using optical methods and high speed recording, we obtained the parameters of sprayed liquid-flow as well as the processes involved in the interaction between liquid aerosol and the decomposing forest fuel. The experimental study helped us establish how much time and quenching liquid is sufficient to suppress the forest fuel combustion. Furthermore, we determined the influence of the forest fuel volume on the conditions and characteristics of the processes under study. Finally, we identified the main physical principles of the thermal decomposition of forest fuel when using the proposed approaches to spraying water into the combustion zone. The research findings enable the optimization of aerial firefighting in terms of wildfire containment and suppression.

Key words: *forest fuel, thermal decomposition, extinguishing, water aerosol*

Introduction

Forest fires lead to colossal environmental and economic consequences [1]. Losses caused by forest fires are regarded among the most severe [2]. Fire extinguishing in the boreal zone usually takes a long time. Fire may spread over large areas. Fire suppression is not always effective, because the diurnal fire cycle also affects the fire elimination process. Fire containment and elimination as well as the deceleration of the fire front spread traditionally involve dropping the extinguishing liquid into the combustion zone by aircraft (planes, helicopters, and drones). Estimating the amount of water necessary to stop the forest fuel (FF) thermal decomposition (a *consumed liquid*), is an urgent task, because the use of aviation for firefighting in the boreal forests is very cost-intensive (in terms of finance, time, labor*, etc.*) [3]. Water dropped by aircraft usually reaches the burning surface as a polydisperse aerosol [4, 5]. Research findings [6, 7] show that the bulk of the liquid supplied this way passes into the ground on limited (extremely small) surface areas and does not suppress the pyrolysis in the layers of the boreal zone over wide areas (the flame bypasses wetted areas along the perimeter). It has been established

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[6, 7] that only 5-7% of the total water can evaporate during the suppression of combustion and pyrolysis of FF. We studied the factors affecting the moisture content of FF as well as the destruction of FF with different moisture content [8]. It is important to analyze the principles of heat and mass transfer and phase transformations in the thermally decomposing FF exposed to different patterns of water spraying (pulsed and continuous irrigation, which enable us to reproduce all the possible conditions of fire extinguishing liquid supply to the forest zone).

The aim of this paper is an experimental research of the main differences between physical processes and phase transformations in the pulsed and continuous supply of liquid aerosol to the FF combustion zone.

Experimental set-up and procedure

Figure 1 shows the scheme of the experimental set-up used to explore the extinguishing of the standardized FF fire. This system recorded the parameters of fast processes. It was equipped with technical means for temperature measurement and high speed video recording, as well as a software and hardware measurement system using panoramic optical methods to test multi-phase media.

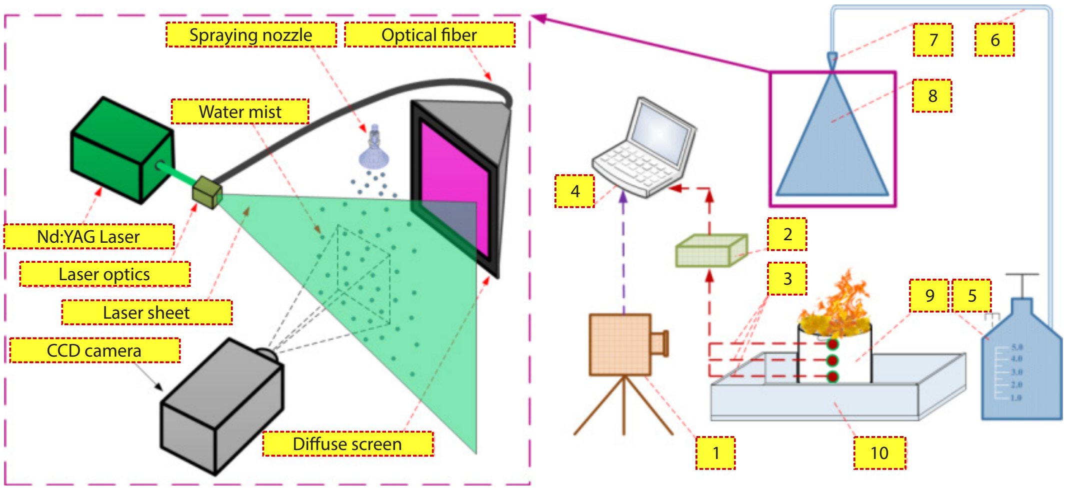

Figure 1. A scheme of experimental set-up: *1 – high speed video camera, 2 – high speed analog input module, 3 – thermocouples, 4 – workstation (PC), 5 – water tank, 6 – water supply channel, 7 – spraying nozzle, 8 – liquid aerosol, 9 – cylinder with an FF sample, 10 – metal tray*

Forest fuels

We used typical FF [9] for our research: birch leaves; and mixed FF with the following mass ratio: 25% birch leaves; 15% pine needles; 60% branches of hardwoods. The samples used for research were pre-dried for a week at a temperature of about 300 K. Immediately before a series of experiments, the moisture content of the materials was determined using thermal drying method. For these purposes, the FF was crushed, weighed and then placed in a drying oven at a temperature of about 375 K for 2-3 hours. After drying, the sample was cooled and re-weighed. The relative FF moisture content FF was determined by formula:

$$\gamma_f = \frac{m_{\text{fw}} - m_{\text{fd}}}{m_{\text{fw}}} 100 \tag{1}$$

The relative FF moisture, γ_f, in our experiments was 5-8% for birch leaves and 8-12% for an FF mixture.

Hollow cylinders made of corrugated aluminum with a height, h_f, and diameter, d_f, fig. 1, were used to create model fire sources. Diameter, d_f, was varied in the range from 20-100 mm, height, h_f, was varied in the range from 40-100 mm. A 3 mm wide vertical hole was made in the cylinders to visually monitor the thermal decomposition of FF.

Before each experiment, the FF sample was weighed on an analytical microbalance to determine its mass, m_{f0}. After that, the sample was placed to the bottom of the cylinder 9, fig. 1. See tab. 1 for the initial weights of the FF samples.

Table 1. Initial weights of FF samples (m_{f0}, g)

Height of fuel bed, h_f, [m]	Diameter of brazier, d_f, [m]	m_{f0},g	
		Birch leaves	FF mixture
0.04	0.02	0.7-0.9	0.9-1.3
0.04	0.04	1.3-1.6	1.9-2.3
0.04	0.06	2.2-2.6	3.2-3.9
0.04	0.1	7.4-7.9	8.6-10.0
0.07	0.06	4.5-5.2	6.4-7.6
0.1	0.06	6.9-7.5	10.4-12.3

The choice of the density of the fuel sample is derived from the densities of forest litter burning out in a surface fire. Forest litter formed over the years has a higher density than a fresh one [10]. The initial weight of FF sample was chosen so that its density varied from one experiment to another in a narrow range (typical for boreal zone): ρ_f = 21-64 kg/m^3 for birch leaves and ρ_f = 30-87 kg/m^3 for mixed FF. The fuel density in the sample was calculated by formula:

$$\rho_f = \frac{m_{f0}}{h_f S_f} \quad \text{where} \quad S_f = \pi\left(\frac{d_f}{2}\right)^2 \tag{2}$$

At lower densities, ρ_f, we registered a very rapid fuel burnout. For higher densities, slow burning was observed, often in the smoldering mode. In some cases, especially with densely pressed birch leaves, the fire spontaneously went out.

Aerosol flow

We used distilled water (the component composition corresponded to the Russian regulatory document GOST 6709-72) for extinguishing the model fire. This way we eliminated the influence of various impurities in tap water on the conditions and characteristics of the studied processes. The angle of the spraying nozzle opening is about 300 K, pressure in the water supply channel P = 2.5 atm. The droplet size in dispersed stream *8* was determined by a diagnostic system using a panoramic optical method known as shadow photography (SP) [11]. A diffusing screen, fig. 1, connected by an optical fiber to a pulsed Nd: YAG laser was placed behind the droplet flow. The diffusing screen was equipped with an optical diffuser for uniform spatial scattering of the laser radiation and was used for background illumination of droplets in liquid aerosol – 8. To register the droplet images, we used a cross correlated CCD camera with a macro lens equipped with a light filter (to prevent the laser from damaging the matrix of the video camera). The camera was installed in front of droplet flow 8 opposite the diffusing screen. The obtained images of droplet stream were transferred to computer – 4 and processed using the ActualFlow software to obtain histograms with the droplet size distribution, radii R_d, in the sprayed flow.

Recording tools of experimental set-up

As the main recording equipment of the set-up, fig. 1, we used:

- A high-speed digital CMOS video camera Phantom V411 with a recording frequency of $6 \cdot 10^6$ fps and maximum resolution of 1280×1280 pixels.
- A high-density thermocouple input module National Instruments NI 9219 with a minimum polling rate.
- Fast-response (thermal delay time no more than 1 s) XA (K) thermoelectric converters.
- Personal computer.
- ViBRA HT 84RCE laboratory microbalance with an accuracy of 10^{-5} g); particle image velocimetry system featuring a signal synchronizer, laser radiation generator, a QUANTEL EverGreen 70 dual-pulse laser, and an IMPERX IGV B2020M cross-correlation video camera.

Research procedure

At the first stage of the experiments, cylinder – 9 with an FF sample was placed on non-combustible metal tray – 10. Three K-type thermocouples (temperature range 223-1473 K, accuracy ±3 K, heat retention no more than 0.1 seconds) were set on the symmetry axis of cylinder – 9. Thermocouples with a junction diameter of 0.2 mm were used. After that, we ignited the model fire source and started the countdown on the electronic stopwatch with a time step of 0.01 seconds. The total burnout time, t_b, of the entire fuel sample was recorded from the start of combustion the moment when the temperature readings of all the three thermocouples exceeded the thermal decomposition temperature T_{if} = 370 K). The moment when the temperature in the reaction zone dropped below this value, was considered the end of the thermal decomposition. The choice of this value is due to the corresponding limit temperatures of the FF thermal decomposition. When the temperature in the fuel bed exceeded this value, this meant stable burning of FF, fig. 2. A 3 mm wide vertical hole was made in the cylinders to visually monitor the thermal decomposition of FF.

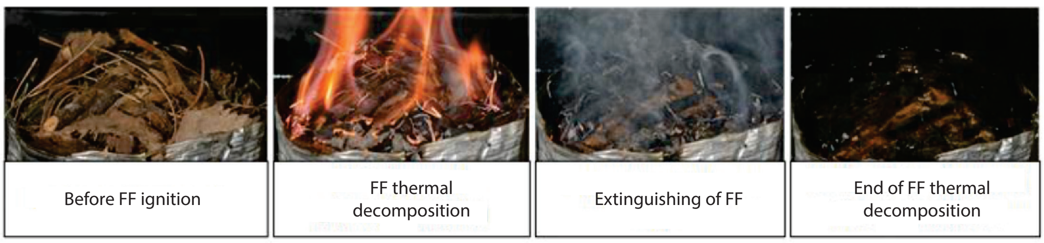

Figure 2. Video frames of the extinguishing the FF sample (birch leaves; and mixed FF with the following mass ratio: 25% birch leaves; 15% pine needles; 60% branches of hardwoods)

At the second stage of our experiments, model fire sources were extinguished by liquid aerosol [12, 13]. The extinguishing times, t_e, were recorded. The fire suppression was considered effective if the inequality $t_e \ll t_b$ was valid. The experimental parameters were droplet radii R_d = 0.01-0.12 mm, initial speed $U_d \approx 2$ m/s, concentration $\gamma_d \approx 3.8 \cdot 10^{-2}$ l/m^3, consumption $\mu_d \approx 0.00035$ l/s. We used the particle image velocimetry, SP, interferometric particle imaging

(IPI) panoramic methods (similar to experiments [11]) for monitoring the water flow parameters (U_d, γ_d, R_d, μ_d). Systematic errors: U_d – 0.005 m/s; γ_d – $2\cdot10^{-3}$ l/m^3; R_d – 0.0015 mm; μ_d – 0.00003 l/s. Typical droplet size and quantity distributions in an aerosol cloud are shown in fig. 3.

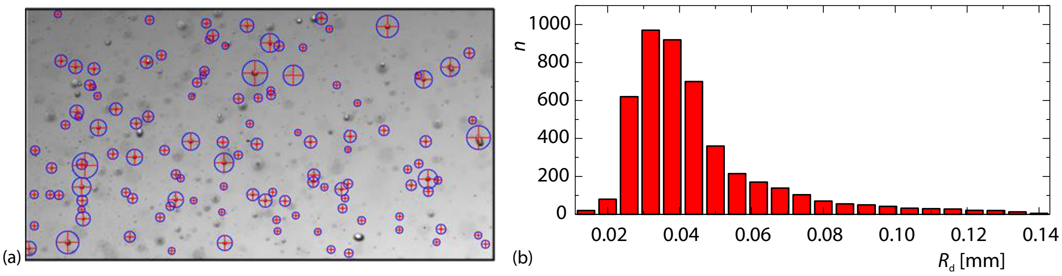

Figure 3. Experimental video frame with selected droplet images (a) and a typical histogram with droplet sizes and their number (according to analysis of 400 frames) as part of the aerosol flow (b), obtained using the SP method

A system consisting of spray nozzle – 7, container with water under pressure – 5 and a supply channel were used to generate disperse flow – 8. Within 10-15 seconds (enough time for the ignition of the entire sample) after the ignition of the model fire source, the shut-off valve was opened. Water from tank – 5 was fed to spray nozzle – 7 through supply channel – 6 until the complete suppression of the standardized fire. The latter was recorded by thermocouple readings and manually. The second stage of experiments is described in fig. 4.

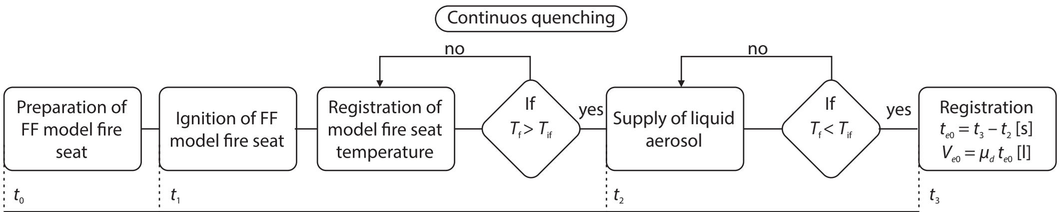

Figure 4. Structure of the second stage of experiments

As a rule, fixed-wing aircraft and helicopters refill water several times during wildfire containment and suppression. During the intervals between drops, fire may reignite in the areas subject to extinguishing and adjacent to them. Pulsed water supply will significantly decrease the amount of water spent on reducing the temperature of the gas-phase combustion and decomposition of FF [14]. The main ways to suppress FF combustion and pyrolysis may rely on supplying liquid aerosol at fixed (short) intervals. This method of feeding the extinguishing liquid will make it possible to stop the combustion and decrease the temperature gradient in the pyrolyzing fuel bed. Short-term pulsed water supply is also possible. The application of this scheme will provide an opportunity to use complete evaporation of the dropped liquid during the gas-phase and heterogeneous combustion of FF [9, 15].

At the third stage of the experiments, a series of tests determined the minimum (sufficient) volume of the quenching liquid to suppress the thermal decomposition of the FF under study in two quenching schemes. Under Scheme No. 1, the liquid aerosol was sprayed at limited intervals (pulsed mode). Fire suppression was monitored visually and using thermocouple readings. The time of continuous liquid aerosol supply until complete fire suppression was taken as the initial interval, which was then decreased in steps of 5-10 seconds. During the experiments, the spraying interval decreased to values, at which the pyrolysis reaction could not be stopped. The spraying interval, which was the closest to the time, during which the thermal decomposition could not be stopped, was taken as necessary and sufficient. According to Scheme No. 2, the liquid aerosol was supplied in small portions and was only resumed when the temperature in the combustion zone increased. A decrease in the temperature of the fuel bed was registered from the thermocouple readings. As soon as the temperature of the heated layer began to decrease, the supply of aerosol was suspended. When the temperature increased, the spraying process was resumed. The pulsed feed of the extinguishing liquid continued until the thermal decomposition in the fuel bed ceased completely. Figure 5 shows schemes for carrying out the experiments according to Scheme No. 1 and No. 2.

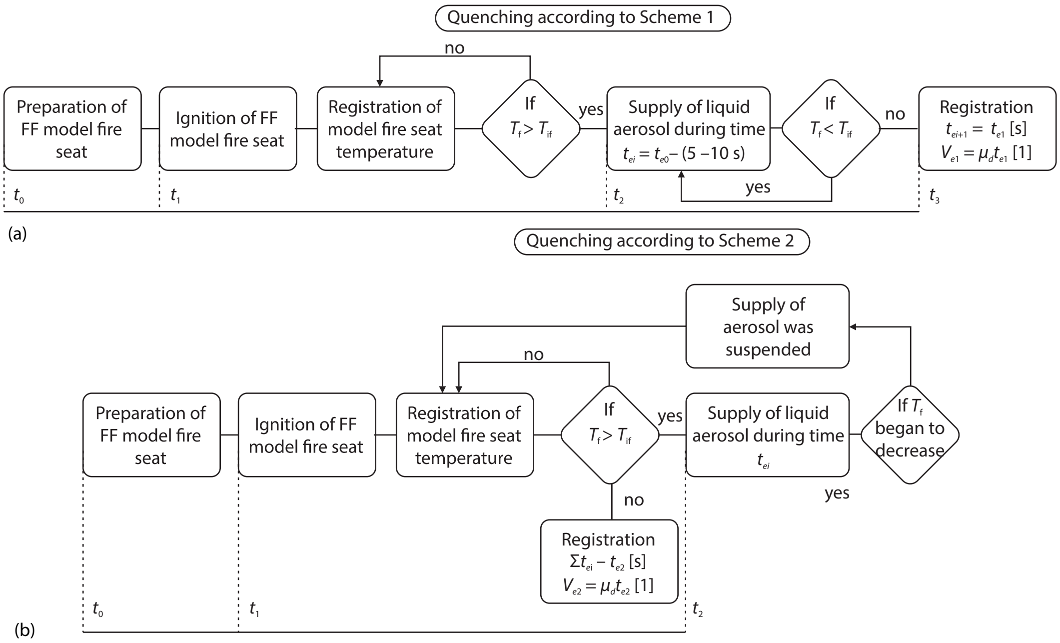

Figure 5. Structure of the third stage of experiments; (a) Sheme No. 1, (b) Sheme No. 2

We carried out 15 to 20 experiments for each model fire source with the corresponding type of FF. Then we sampled the experimental values of t_b or t_e differing by less than 5% for identical experimental conditions. The systematic errors were $7 \cdot 10^{-6}$ m in determining the dimensions R_d of drops, 0.5 second for the times t_e and t_b, $5 \cdot 10^{-4}$ l for volume, 0.01 m/s for the velocities of droplet movement in aerosol U_d, and 0.00002 l/s for water consumption μ_d. The maximum random errors in determining temperatures during thermal decomposition T_f were no more than 30 K.

Results and discussion

Figures 6 and 7 show the input water volumes for continuous spraying of a liquid aerosol and the minimum water volumes required for quenching the Schemes No. 1 and No. 2 with a variation in the diameter, d_f, and height, h_f, of model fire sources containing different types of FF. Burnout times, t_b, for models of fire source with birch leaves was 100-250 seconds and 130-390 seconds for FF mixture according to the changes d_f. During variation the height of models of fire source h_f burnout time was 200-350 seconds for birch leaves and 260-400 seconds for FF mixture.

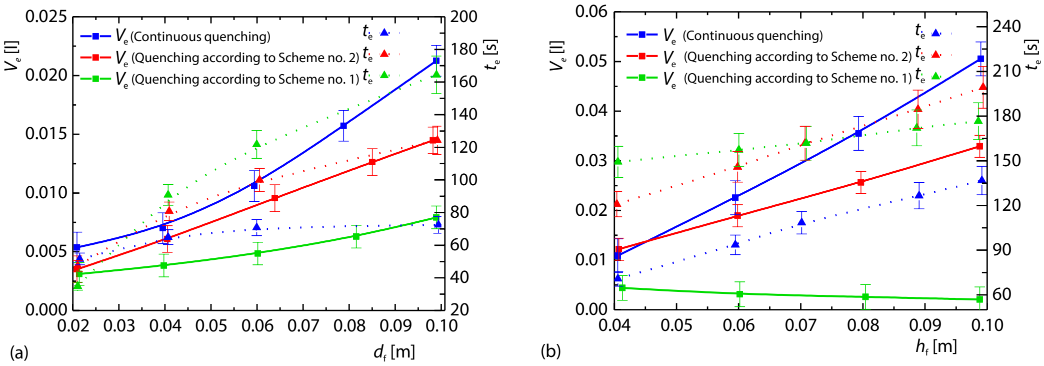

Figure 6. Water volume, V_e, consumed to extinguish the model fire source (birch leaves) and the respective times, t_e, with variable diameter, d_f, and constant $h_f \approx 40$ mm; (a) as well as with variable height, h_f, and constant $d_f \approx 60$ mm (b) using liquid aerosol (R_d = 0.1-0.12 mm)

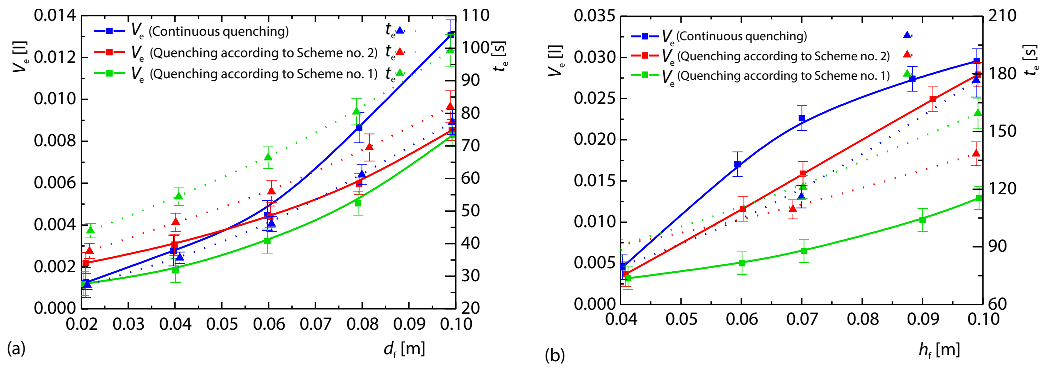

Figure 7. Water volume, V_e, consumed to extinguish the model fire source (mixed FF) and the respective times, t_e, with variable diameter, d_f, and constant $h_f \approx 40$ mm; (a) as well as with variable height, h_f, and constant $d_f \approx 60$ mm (b) using liquid aerosol (R_d = 0.1-0.12 mm)

Analysis of the dependencies presented in figs. 6 and 7 enables us to conclude that a continuous liquid aerosol supply to a model fire source can suppress the thermal decomposition in the shortest time but using maximum liquid. When sprayed, however, the quenching liquid is mixed with products of thermal decomposition and evaporates to displace gaseous products of pyrolysis. After 15-20 seconds, a vapor cloud forms and prevents the oxidant from entering the reaction zone. However, only a small part of the quenching liquid evaporates when passing through the zone with the products of thermal decomposition. Most of the liquid reaches the surface of the sample. Water droplets accumulated on the surface of FF during its pyrolysis and penetrated into its pores, thereby reducing its temperature. Thus, we implemented one of the three main (determining) mechanisms for stopping the pyrolysis of the material.

The type of FF also had a significant effect on the conditions for suppressing its thermal decomposition. We have established that birch leaves required the minimum V_e for continuous spraying variation the height of models of fire source. The maximum V_e in the experiments was recorded for the mixed FF. When spraying water on the model fire sources consisting of twigs, leaves and needles the water volume, V_e, reaches its maximum value for several reasons. Firstly, each twig burned for a much longer time than foliage and needles before reaching the smoldering stage. Secondly, the diameter of the twigs reached 3-5 mm. As a result, the front of the thermal decomposition passed deep into the material. This explains the largest values of V_e. The minimum volumes spent on suppressing the reaction of birch leaf destruction can be explained by the fact that the structure of the leaf sample differs from that of the mixture, forming a more homogeneous monolithic bed. Therefore, water accumulated on the surface of the material during continuous spraying, thereby preventing the oxidant from entering the near-surface layer of FF.

Scheme No. 1 more than halved the volume of liquid used for quenching in contrast with Scheme No. 2 and continuous liquid aerosol supply. Most series of experiments using quenching Scheme No. 1 showed that if spraying successfully suppressed the flame burning of the FF under study within the predefined minimum interval, the thermal decomposition ceased. When spraying could not suppress the flame within the predefined time, it was not possible to stop pyrolysis with small water volumes (according to quenching Scheme No. 1). The suppression of gas-phase combustion of the FF under study by supplying a liquid aerosol to the combustion zone within minimum time seems to have decreased the maximum values of the temperature gradient in the bed, so the rate of heat transfer slowed down. The energy inflow was blocked starting from the intensively decomposing section the area with lower temperatures.

The average values of the liquid volumes involved in quenching correspond to Scheme No. 2 (relative to continuous spraying and Scheme No. 1). Pulsed water supply to the reaction zone intensifies the endothermic phase transformations with almost complete evaporation of quenching liquid in the reaction zone. In this case, evaporation is the dominant mechanism for suppressing the process of FF destruction.

Furthermore, a series of experiments helped us record the time needed for the thermal decomposition of FF to cease. The obtained results, figs. 6 and 7, lead to a conclusion that using a liquid aerosol to extinguish the model fire sources is effective, because the registered values of t_b for the investigated FF are much longer than t_e.

The minimum quenching time with the continuous supply of a liquid aerosol is recorded for the 40 mm high model fire source with a variable diameter, d_f, figs. 6(a) and 7(a). The maximum time intervals are typical of Scheme No 1. Quenching according to Scheme No. 2 is characterized by the average volumes of the liquids and times necessary for the suppression of the thermal decomposition. The minimum times of model fire suppression were obtained by continuous spraying of a liquid aerosol. However, the amount of water required for quenching by this method is maximum. The minimum volumes involved in quenching correspond to the quenching Scheme No. 1 but the time required to stop the sample reaction is longer relative to the time in other extinguishing schemes.

Figures 6(b) and 7(b) also illustrate the times needed to terminate the thermal decomposition of birch leaves and mixed FF by spraying liquid on the model fire sources with a diameter $d_f \approx 60$ mm and variable height, h_f.

It is fair to say that the difference between the times of fire suppression and thermal decomposition of FF depends on the structure of the sample. Samples from birch leaves had a more homogeneous structure and, thus, the aerosol droplets settled on the upper foliage layer and the burning of the material ceased. Then, a thin liquid film formed on it, water began to penetrate into the next (lower) layer and so on. Thus, the suppression of in-depth thermal decomposition of the leaf sample took much more time than the same process for needles and twigs.

The thickness, h_f, and the diameter, d_f, of the FF samples had a significant influence on the quenching characteristics, t_e and V_e. At first sight, these results may seem obvious but we have established some interesting features. When d_f is varied from 0.02-0.1 mm, the values of the parameters t_e and V_e increase several times. With d_f increasing, the surface area of the FF sample increases and so does the heat content of the model fire sources, because the heat removal from the pyrolysis zone to the outer walls is maximum for small d_f. Consequently, an increase in d_f accelerates the thermal decomposition in the central part of the sample relative to the peripheral zone. The combustion products blown from the FF surface acquire a greater speed. Some water droplets evaporate in the flame or are carried away by the combustion products of the standardized fire. Therefore, it takes much more time and water to suppress the thermal decomposition process. It has been established that the thickness of the sample h_f affects the times needed to suppress the thermal decomposition of FF, figs. 6 and 7. Thus, when the thickness of the sample varies from 0.04-0.1 m, the suppression of the decomposition reaction takes more time. It can be assumed that the determining effect was exerted by the heat content of the reacting fuel bed. The FF residue after the experiments with a thickness, h_f, ranging above 0.07 m was less than 5%. Most of the fuel sample could not be saved from burning out. The experiments only made it possible to suppress the thermal decomposition within a much shorter time than that of FF burnout. Such pattern was not observed when the diameter of the sample was varied. Most of the sample could be saved, which may be due to an increased area, on which the liquid aerosol is sprayed. With minimum and sufficient water, figs. 6 and 7, according to quenching Scheme No. 1, the thermal decomposition ceased within the following times, for example:

– for birch leaves

61-83 seconds sample with a thickness h_f = 0.04 m and diameter d_f = 0.04 m
124-167 seconds – sample with a thickness h_f = 0.04 m and diameter d_f = 0.06 m
135-164 seconds – sample with a thickness h_f = 0.04 m and diameter d_f = 0.1 m
171-189 seconds – sample with a thickness h_f = 0.1 m and diameter d_f = 0.06 m

– for mixed FF

42-65 seconds sample with a thickness h_f = 0.04 m and diameter d_f = 0.04 m
62-78 seconds sample with a thickness h_f = 0.04 m and diameter d_f = 0.06 m
92-108 seconds sample with a thickness h_f = 0.04 m and diameter d_f = 0.1 m
110-136 seconds sample with a thickness h_f = 0.1 m and diameter d_f = 0.06 m

Figure 6 shows the curves of temperature change in the fuel bed according to quenching Scheme No. 2. With birch leaves, no matter how large the model fire source was, it took one to two pulses to contain and suppress the thermal decomposition of FF, fig. 8(a). In the case of mixed FF, fig. 8(b), the entire process of quenching required three to seven pulses depending on the burning intensity of the twigs. The duration of one pulse could vary from 7-10 seconds to 50-60 seconds, respectively. As a rule, the longest pulses corresponded to the initial stage of the quenching process, fig. 8. The shortest ones, on the contrary, were observed at the final stages of the investigated process.

As a result of the experimental data analysis, we obtained dependencies and approximations. These enable us to predict the necessary conditions depending on the priority of the forest fire extinguishing factors, tab. 2.

To reduce the extinguishing time, tab. 2, we can recommend continuous spraying of extinguishing liquid into the combustion zone although with maximum water consumption. The experiments enabled us to detect the corresponding differences in the water volumes used. The established dependencies make it possible to predict (according to approximate expressions) the water volumes necessary for suppression of the thermal decomposition over large areas comparable to those in a real fire. In terms of rational extinguishing liquid consumption, we can give priority to the spraying method according to Scheme No. 1, tab. 2. This way, the thermal decomposition of FF is suppressed during maximum intervals established in the experiments but with minimum (sufficient) volumes of liquid.

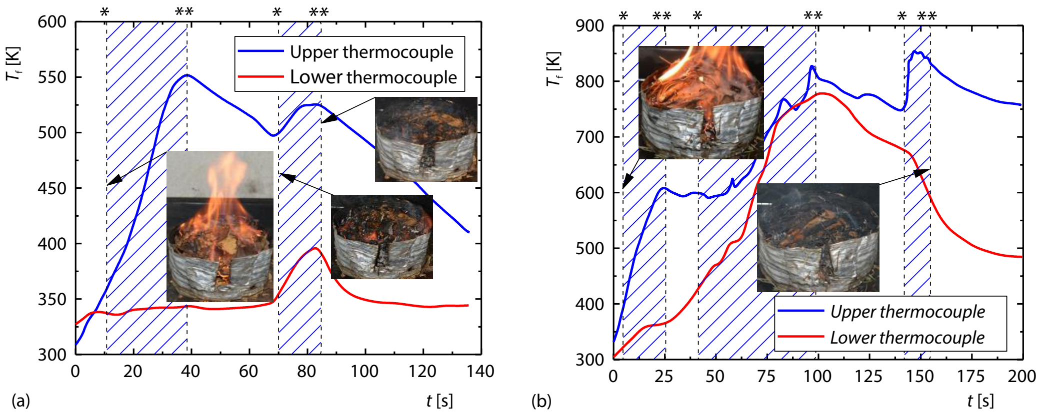

Figure 8. Curves of temperature change in the fuel bed with a thickness of the sample $h_f \approx$ 40 mm and diameter $d_f \approx$ 60 mm during extinguishing with liquid aerosol (R_d = 0.1-0.12 mm) using extinguishing Scheme No. 2; (a) birch leaves, (b) mixed FF; *the shaded area corresponds to the spraying period of the water aerosol. Symbols * and ** characterize the beginning and the ending of the spray process*

Table 2. Priorities and conditions for extinguishing model fire sources

Type of FF	Priority task	
	Min, t_e	Min, V_e
Birch leaves	Continuous extinguishing: $V_e = 9.08 \cdot 10^{-4n} + 29.7 \cdot 10^{-4}\exp(19.45d_f)$ $V_e = -0.095 + 0.084\exp(5.47h_f)$	Quenching according to Scheme No. 1: $t_e = 396.28 + 103.91\ln(d_f + 0.0105)$ $t_e = 262.69 + 41.15\ln(h_f + 0.0203)$
Mixed FF	Continuous extinguishing: $V_e = -28.1 \cdot 10^{-4} + 28.2 \cdot 10^{-4}\exp(17.48d_f)$ $V_e = -0.036 - 0.093\exp(-26.97h_f)$	Quenching according to Scheme No. 1: $t_e = -9.526 + 43.682\exp(9.228d_f)$ $t_e = -7.626 + 67.7\exp(9.107h_f)$

Conclusion

As a result of the experiments for the first time it was possible to reliably determine the minimum (sufficient) volume of the quenching liquid to suppress the thermal decomposition of the FF under study in two quenching schemes. Under Scheme No. 1, the liquid aerosol was sprayed at limited intervals (pulsed mode). According to Scheme No. 2, the liquid aerosol was supplied in small portions and was only resumed when the temperature in the combustion zone increased. The main result of the research is that each of the two schemes can be effective for different FF types. These patterns are demonstrated by the example of the birch leaves and mixed FF with the following mass ratio: 25% birch leaves; 15% pine needles; 60% branches of hardwoods. The key result of the research is that by using scheme of dosed water supply to the combustion zone it is possible to significantly reduce the flow rate of extinguishing liquid and optimize the combustion suppression. This study shows that these conditions are fulfilled for FF samples with different sizes and properties, as well as for droplet aerosols with different droplet sizes and volumes of liquid. Therefore, the results of research can be applicable in the development of schemes for localization and suppression of real forest fires.

Acknowledgment

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Nomenclature

d_f, h_f – diameter and height of FF sample, [m]
m_{f0} – initial mass of FF before thermal drying, [g]
m_{fd} – mass of FF after drying, [g]
m_{fw} – mass of wet FF (before drying), [g]
n – number of droplets
P – pressure in the water supply channel, [atm]
R_d – droplet radius, [mm]
S_f – surface area, [m^2]
T_f – temperature in FF layer, [K]
T_{if} – temperature of thermal decomposition intensification, [K]
$t_{0...3}$ – time of stages in experiments, [s]
t_b – time of burnout of FF without water supply, [s]
t_e – time of suppressing the thermal decomposition of FF, [s]
$t_{e0...3}$ – time of suppressing in different experimental stages, [s]
U_d – droplet velocity, [ms^{-1}]
V_e – water volume consumed to extinguish, [l]

Greek symbols

γ_d – volumetric concentration of aerosol droplets, [lm^{-3}]
ρ_f – packing density of FF in the sample, [kgm^{-3}]
μ_d – water consumption, [ls^{-1}]
γ_f – relative FF moisture content forest fuel, [%]

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