

# FIRE EXTINCTION OF FOREST FUELS BY DROPLETS AND WATER FILM

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*Paper presents the experimental results about fire extinction in the model fire sites of forest combustible materials. We use the high-speed video recording tools during the experiments, as well as the system of multiphase media diagnostics based on panoramic optical flow visualization techniques. The presented experiments prove that it is possible to extinguish the forest combustible material (FCM) by small amount of water. The study considers several ways to stop FCM thermal decomposition: by individual large water droplets (1–3 mm), by an aerosol flow (the droplet size is from 0.05 mm to 0.12 mm), or through water film formation on the FCM surface. Typical durations of the FCM thermal decomposition and time of fire suppression are determined for various conditions of interaction with water. The experimental results identify which amount of water is enough to extinguish the FCM by different ways of water transfer to the reacting surface layer. Furthermore, it is estimated how the component composition and the properties of the tested FCM mixtures effects onto the characteristics of the investigated processes. The residual fraction of the FCM was evaluated by comparison of initial and final (after extinguishing) mass of the sample.*

Keywords: *forest combustible material, fire, thermal decomposition, extinguishing, water mist, spray.*

## 1. Introduction

The problem of extinction of the forest fires has been perhaps the most urgent topic for many years [1–4]. Forest fires destroy annually millions of hectares of forests, thus the entire ecosystems have disappeared. In addition, the incidents of recent years in Khakassia, Transbaikal and Buryatia (Russia) have showed how dangerous ground fire can be. Fire propagates through ground cover, so buildings and houses are quickly engulfed in flames. As a result, forests and several residential villages were totally burned.

To date, the main process in forest firefighting is not extinction, but fire localization (to prevent further possible propagation). Protective bands (ditches) are used to prevent the fire propagation. The fire front is irrigated by tons of water with the help of aviation when it is impossible to make such bands [2]. However, this approach does not allow localizing the fire propagation and moreover extinguishing the FCM fire site. This is due to the fact that a water mass (fire-extinguishing liquid) usually covers a quite limited FCM surface area [3]. In addition, recent theoretical studies [5, 6] have shown that when large water masses are locally discharged to a fire site, about 90–95% of the liquid is involved in firefighting inefficiently. In this case, almost entire volume of water passes through the flame combustion zone without evaporation. In other words, the extinguishing liquid is not

virtually involved in fire suppression. This illustrates the substantial limitations of applicability of this approach and its low efficiency. All these facts require to improve the efficiency of water consumption in firefighting. Some specialized methods have been developed for this purpose [7]. For example, it can be delivered in the form of water mist, water spray, vapor curtain, etc. Such approaches were used in various fire extinguishing systems, but usually, it was used in a confined space, which is typical for building fire. Reliable experimental data on the usage of such systems for fire extinction of FCM have not been published yet.

The experimental studies [8] demonstrate that it make a sense to spray fine water droplets which can essentially reduce the temperature in the flame combustion zone and intensify the vaporization. In this case, several mechanisms of oxidation suppression occur simultaneously: the temperature decreases due to heating of relatively cold water; flame energy is absorbed during evaporation of the liquid; water vapor blocks the delivery of an oxidant to the combustion zone. Most of the flame energy is absorbed due to the heat effect of water vaporization (2.26 MJ/kg). The flue gas temperature is reduced to 300–500 K relatively to the initial flame temperature (which corresponds to the average fire temperature and is about 1170 K) [5, 6]. The heat content of the gas-phase combustion of typical FCM (birch leaves, pine and spruce needles) is ten times greater than the heat content of the FCM superficial layer heated up to high temperatures (over 600 K) [5, 6]. In order to reduce the temperature of the FCM pyrolysis to 350–500 K (corresponding to the start of thermal decomposition), it is required no more than 3% of water that is needed for suppression of gas-phase combustion [5]. The typical size of the gas-phase combustion zone can reach 10–15 m. The thickness of the heated FCM layer is not more than 0.1 m (usually, it varies from 0.02 m to 0.06 m) under real forest fire conditions.

Numerical studies [5] have shown that a water film with a thickness 1–3 mm on the FCM surface is enough to suppress FCM thermal decomposition. However, experimental results justifying this conclusion have not been published so far. Also, there are not any experimental studies proving the results of [5] about the specific volume of the liquid (several tens of microliters per 1 m<sup>2</sup>) sufficient to extinguish fire in the FCM.

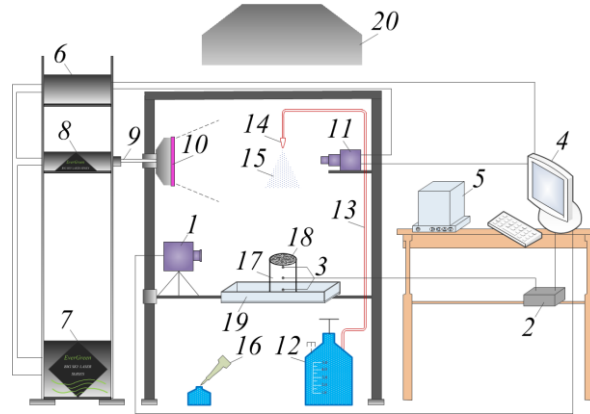
The aim of this study is an experimental determination of the sufficient conditions for extinguishing of the model fire sites consisting of a mixture of typical FCM by the set of droplets, water film, and an aerosol flow.

## 2. Experimental setup and procedure

Fig. 1 shows the scheme of the experimental setup used for studying the extinction of the FCM fire sites. The setup represents a system designed for the registration of fast process parameters [8]. The facility is equipped with temperature measurement devices, high-speed video recording tools, as well as the software and hardware complex for measurements by the panoramic optical techniques of multiphase media diagnostics [8]. The first group of equipment includes: a high-speed (minimum sampling rate is 0.1 s) analog input module National Instruments NI 9213 2 for temperature sensors connection; low-inertia (thermal lag is no more than 1 s) thermocouples of type K 3. The second group includes the cameras Phantom V411 and MIRO M310 1 (frame rate is up to 6·10<sup>6</sup> fps).

The hardware-software complex includes the following equipment: a signal synchronizer 6 (signal sampling is no more than 10 ns, supporting modes of external and internal triggering), double-pulse solid-state Nd: YAG laser QUANTEL Ever Green 70 8 (wavelength is 532 nm, pulse

energy is up to 74 mJ, pulse duration is approximately 12 ns, repetition rate up to 15 Hz) complexed with a power laser generator 7, a cross-correlation CCD video camera IMPERX IGV B2020M 11 (image format is 2048×2048 pixels, frame rate is not less than 1.5 Hz, delay between two frames is from 5 μs to hundreds of milliseconds), optical fiber 9 and diffuse screen 10. A computer 4 is included to store and process the results of experiments. A microbalance ViBRA HT 84RCE 5 (increments is 10<sup>-5</sup> g) is used to control the mass of the forest combustible material (FCM) sample.



**Figure 1. Scheme of experimental setup: 1 – high-speed camera; 2 – high-speed analog input module; 3 – thermocouples; 4 – workstation; 5 – laboratory microbalance; 6 – signal synchronizer; 7 – laser generator; 8 – solid double-pulse laser; 9 – optical fiber; 10 – diffuse screen; 11 – cross-correlation camera; 12 – water container; 13 – water supply channel; 14 – spray nozzle; 15 – water mist; 16 – electronic single-channel dispenser; 17 – cylinder with FCM sample; 18 – FCM; 19 – metal tray; 20 – ventilation**

We have tested the mixture of typical forest combustible materials: birch leaves, pine needles, and twigs of deciduous trees (birch, aspen). The twigs were preliminary dried for 3–5 days at a temperature of about 300 K. The wetness of materials was determined by a thermal drying method immediately before the series of experiments. For this purpose, we ground up the tested FCM, pre-weighed it in the balance and then placed to a drying oven for 2–3 hours at a temperature of about 305 K. The dry sample was cooled and re-weighed. The relative wetness of FCM was determined by the formula:  $\gamma_f = (m_{fw} - m_{fd}) / m_{fw} \cdot 100$ . In the experiments, the relative wetness  $\gamma_f$  of tested FCM was: 5–8% for birch leaves; 7–10% for pine needles; 10–14% for twigs of deciduous trees (birch, aspen).

Model of fire sites were created in special hollow aluminum cylinders (height  $h_f$ , diameter  $d_f$ ) 17. The parameter  $d_f$  varies between 20 mm and 150 mm, and  $h_f$  – between 40 mm and 100 mm. A vertical cut with a width of about 3 mm was made at the one side of the cylinders. It ensures visual observation of the FCM thermal decomposition. Model fire sites were filled with a FCM mixture with the following mass ratio of the components: 25% of birch leaves; 15% of pine needles; 60% of twigs of deciduous trees. Before each experiment, the FCM sample was weighed in the analytical microbalance 5 (to determine the mass  $m_{f0}$ ). Then, FCM 18 was placed to the bottom of the cylinder 17. The initial weight of the FCM was chosen so that its density  $\rho_f$  was varied in a fairly narrow range:  $\rho_f = 75\text{--}85 \text{ kg/m}^3$ . The density of the FCM in the sample was calculated by the formula:  $\rho_f = m_{f0} / (h_f \cdot S_f)$ ,  $\text{kg/m}^3$ ,  $S_f = \pi \cdot (d_f/2)^2$ . Individual successive droplets were generated by an electronic single-channel dispenser 16 Finnpiptette Novus (volume range is from 10 μL to 100 μL, increments is 0.1 μL). The maximum generation rate is 1 droplet per 1.5 seconds. Water mist droplets (with radius 0.01–0.1 mm) were generated by a set of special spray nozzles 14.

The model fire site was evenly ignited over the entire area of the FCM exposed surface. It was achieved by the simultaneous operation of three piezoelectric gas burners. The process of FCM thermal decomposition has several stages. In the case of birch leaves and pine needles, the FCM sample burns completely over the height of the cylinder 17 (the burning time does not exceed 150 seconds for all sizes and heights of model fire sites). Moreover, fiery burning often ends before the burnout of the FCM sample. Then, the entire FCM sample continues to smolder till its complete burnout. In the case of experiments with twigs, we can distinguish two characteristic phases of thermal decomposition. The first phase is fiery burning of the material; the second one is smoldering until the complete burnout of the entire FCM.

We have carried out the experiments in two stages. In the first stage, we have determined the times  $t_b$  and examined the burnout features of the FCM model fire sites. In the second stage, we have found the times of fire sites extinction  $t_e$  under different conditions of water delivery to the FCM.

The first stage has included the following procedures:

- the cylinder 17 with the FCM sample was placed on then on-flammable metal tray 19;
- thermocouples of type K 3 (temperature measurement range is 223–1473 K, systematic error is  $\pm 3$  K, thermal inertia is no more than 1 second) were inserted into the cylinder 17 at three points on its height on the axis of symmetry;
- the model fire sites were ignited; an electronic stopwatch (time step is 0.01 s) started timing;
- the time of complete combustion ( $t_b$ ) of the entire FCM was defined (time period from the beginning of combustion till the moment, at which the temperature readings of all three thermocouples become above the temperature of thermal decomposition ( $T_f$ ) 370 K). This value was chosen in accordance with the relevant limit temperatures of the FCM thermal decomposition. The excess of this temperature in the layer relatively to the temperature of the environment was considered as a criterion of FCM stable combustion. We have conducted about 15–20 experiments for each FCM model fire site (the values of  $t_b$  were averaged).

The second stage (of the fire sites extinction) has included three series of experiments:

- 1) the fire site was extinguished by sequential delivery of single droplets with a radius  $R_d \approx 1.5$  mm. Droplets' delivery was continued until the complete fire suppression (the presence of combustion was detected by thermocouple readings and by visual observation). The amount of water spent for extinguishing by single successive droplets was found by the formula:  $V_e = V_d \cdot n$ ;
- 2) the fire site was extinguished by the water mist flow with a droplet radius  $R_d = 0.01$ – $0.1$  mm [8]. Water mist 15 was generated by the system consisting of a spray nozzle 14, container with pressurized water 12 and the delivery channel. After 10–15 seconds after the ignition the model fire site (the time is enough for burning of the entire FCM sample), we have opened a stop valve. Thus, water was fed from the tank 12 to the sprayer 14 through the channel 13. Spraying was continued until complete fire suppression (the presence of combustion was detected by thermocouple readings and visual observation);
- 3) the spraying system was the same as at the previous series. However, water mist 15 was sprayed to the model fire site until the formation of a thin water film on the FCM surface. After that, spraying was stopped. This method of water delivery to the combustion zone can be regarded as a pulsed one. The presence of the liquid film on the FCM surface was detected during the analysis of video frames.

In each experiment, the time of the model fire site extinction was controlled ( $t_e$ ). The time of fire elimination ( $t_e$ ) was compared with the time of the FCM complete decomposition (burnout) ( $t_b$ ),

which was found previously. If  $t_e \ll t_b$ , it was considered that extinguishing conditions are achieved. Also, a share of the unburned FCM (residue) was recorded. The latter was dried for 3–5 hours after fire suppression. After that, the mass of the unburned FCM was measured using the analytical microbalance 5 and was compared with the initial mass.

After each experiment of the second and third series, the excess of the liquid remained in the metal tray 19 was collected to a measuring cup in order to find its volume  $V_s$ . The amount of water spent for extinguishing by water mist was determined by the formula:  $V_e = \mu_w \cdot t_e - V_s$ .

We have conducted at least 20 experiments for each FCM model fire site.

At each experimental series with water mist, we additionally determined (using the software and hardware PIV complex) the sizes ( $R_d$ ) of aerosol droplets and their initial velocities ( $U_d$ ). The velocities  $U_d$  were monitored before the experiment applying the PIV method – the panoramic optical technique of tracer flow visualization [9]. The system was preliminarily calibrated; the CCD camera lens 11 was focused in the measurement area of a particular spray nozzle 14. The following values were selected: the capacity of each modulator of the Nd: YAG laser 8, the size of the camera aperture, and the opening angle and the thickness of laser light beam. The scale factor (mm/pixel) was determined using special devices (calibration target or prism). The videograms (image pairs) of the sprayed extinguishing composition were recorded in the vicinity of spray nozzles. For this purpose, the spray flow was repeatedly dissected by laser light 8 formed by special optics (special divider of laser beam with a collimator fixed on it). The images of highlighted water droplets were captured by the cross-correlation CCD camera 11 (not less than 200 pictures for each experiment). The captured images of the flow were saved in the workstation 4. Then, they were processed using a number of software filters (to eliminate noise) and specialized iterative algorithms for calculating the instantaneous velocity. For each image of the flow, we have defined the movement of droplets during the time between laser flashes. The values were averaged for the same observation areas. Instantaneous drip flow velocities were found.

The sizes  $R_d$  were evaluated by the panoramic optical technique of shadow pictures SP [10, 11]. For its implementation, the following scheme was applied. A diffuse screen 10 was placed in the upper part of the experimental setup (Fig. 1) behind the sprayed flow. It provides a backlighting of liquid droplets. The diffuse screen 10 was connected to the pulsed Nd: YAG laser 8 by an optical fiber 9 (by means of a special splitter of a laser beam mounted on the laser). The screen was equipped with a diffuser in the place of fiber connection. The diffuser have ensured uniform laser light scattering. The CCD camera 11 with a macro lens was installed in front of the diffuse screen.

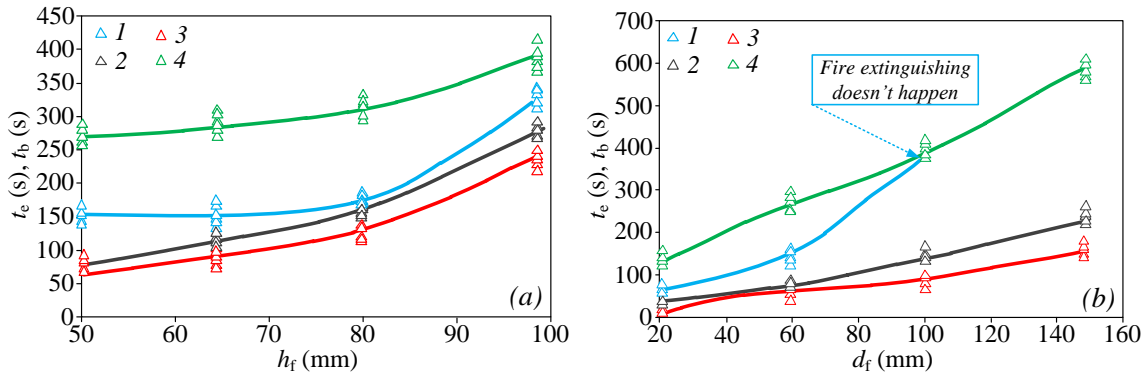
Thus, the drip flow was generated by nozzles 14 and moved strictly between the diffuse screen 10 and the CCD camera lens 11. The emission power of each modulator of the Nd: YAG laser 8 was adjusted. This allows obtaining the necessary contrast of shadow images sufficient for the subsequent identification of droplets in videograms. We took at least 200 pictures of the flow in each experiment. The video recordings were saved in the workstation 4, where they were subsequently processed by software filters Median, Low Pass (to eliminate noise in images) and Laplace Edge Detection (to identify droplet images). The size and number of droplets was defined by the Bubbles Identification algorithm.

The systematic errors at determination of the droplet size ( $R_d$ ) was  $7 \cdot 10^{-6}$  m, 0.03 m/s for velocities ( $U_d$ ), 0.5 s for times  $t_e$  and  $t_b$ , and  $5 \cdot 10^{-4}$  L for volume  $V_e$ . The maximum random error at the determination of the temperatures ( $T_f$ ) during the FCM thermal decomposition did not exceed 30 K.

### 3. Results and discussion

As a result of series of experiments, we have determined the times of model fire sites extinction  $t_e$  (the suppression of the thermal decomposition) depending on the sizes of the model fire sites (height and diameter). Also, we have defined the amount of water  $V_e$  that was spent to stop the FCM thermal decomposition depending on the size of model fire sites. Experimental investigations also gave us the times of the complete combustion (thermal decomposition) of the tested FCM mixture ( $t_b$ ). For example, for  $h_f \approx 40$  mm, the minimum time  $t_b$  was about 130 s (it corresponds to  $d_f \approx 20$  mm). The highest  $t_b$  at  $h_f \approx 40$  mm was detected for  $d_f \approx 150$  mm and it was about 610 s (Fig. 2). Fig. 2a shows the time  $t_e$  depending on the thickness of the FCM sample, when the fire site diameter is  $d_f \approx 60$  mm. Fig. 2b illustrates a similar dependency of time  $t_e$  on the FCM sample diameter, when the fire site height is  $h_f \approx 40$  mm.

The longest times  $t_e$  are detected in the experiments with individual successive water droplets (curve 1 in Fig. 2). This appears due to non-uniform irrigation of the reacting FCM field. For example, when the model fire site was extinguished by single droplets, the flame height was decreased in the places, where droplets fell. Also, there was a noticeable decrease in the rate of the thermal decomposition. At the same time, the FCM thermal decomposition was continued without changes in the areas, where droplets did not fall. The similar effects were observed in the local discharge of water to a combustion zone by aviation. In our experiments, an effective quenching of the FCM was achieved by a uniform irrigation of the entire FCM area by single droplets. They have penetrated into the depth of the material relatively quickly. This process has slowed down the burning process. Moreover, droplets damped the middle layers of the material, thereby preventing flame propagation into the depth of the FCM.



**Figure 2. Time of the FCM total burnout and extinguishing depending on the height of fire site with diameter  $d_f \approx 60$  mm (a), or depending on the diameter of fire site with the height  $h_f \approx 40$  mm (b): 1 – extinguishing by individual droplets (droplet size is  $R_d \approx 1.5$  mm); 2 – extinguishing by water film; 3 – extinguishing by water mist (droplet size is  $R_d = 0.01\text{--}0.1$  mm); 4 – without extinguishing**

The fire extinction times  $t_e$  have fairly close values for both cases when the water film formation on the FCM surface was used and when we have used the water mist (curves 2 and 3 in Fig. 2). This result can be explained by several factors. In the case of extinguishing by water mist, two mechanisms are implemented simultaneously: the material cools down to a temperature of termination of the thermal decomposition ( $T_f \approx 370$  K); atmosphere oxygen is extruded from the combustion zone. Small water droplets seeps into the depth of the burning FCM, thereby cooling it inside and extruding the oxygen from its pores. The water film which is formed on the FCM surface does not allow the

heating of the deeper layers and prevents it from the additional airflow. Besides that, in the initial stage of extinguishing, water mist droplets evaporate intensively at the presence of flame. This contributes to further cooling of FCM and to extrusion of the oxidizer with outgoing water vapor. Thermocouples 3 (Fig. 1) have indicated a decrease of the temperature by 50–70 K in the FCM upper layer during the intensive evaporation of the mist droplets.

The experiments demonstrate that the water film with the thickness of 2 mm is formed already after 30–40 seconds after the start of irrigation of the FCM. Further irrigation does not significantly increase its thickness. To the moment of the water film formation, the droplets seeped into the depth of the FCM layer and therefore cooled the burning material to a temperature below 600 K. This, together with the thin water layer onto the FCM surface, leads to further damping of the model fire site even without its further irrigation. As a result, the time  $t_e$  has values that are very close to effects of the water mist and the water film usage (Fig. 2).

The experiments revealed some features of the investigated processes, in particular, the level of the influence of the diameter ( $d_f$ ) and height ( $h_f$ ) of the FCM fire sites on the characteristics of burnout processes. Thus, it has been found that the growth of  $h_f$  leads to an increase in times  $t_b$  and  $t_e$  (Fig. 2a), regardless to the extinguishing method. The growth of  $t_e$  with increasing  $h_f$  (Fig. 2a) can be explained by following: the growth of the thickness of the FCM layer leads to penetration of the smoldering front deeper into the sample the during thermal decomposition. Moreover, bigger amount of water is required for extinction of the model fire site by single successive droplets or water mist, in order to achieve FCM smoldering (due to the fact that water can propagate very slowly in the FCM pores). As a consequence, it takes longer time  $t_e$ . In the case of extinction of the model fire site by the water film, an increase of the time  $t_e$  with growth of  $h_f$  is primarily due to an increase of the volume of the FCM ( $V_f$ ). Thus, when the  $V_f$  grows, then the number of voids (pores) in the FCM layer grows too, providing a greater supply of an air. Therefore, even though the water film restrains the oxidizer inflow from the external environment, we can say that the FCM thermal decomposition continues until nearly full consumption of the oxidizer reserves. This causes a noticeable growth of  $t_e$  values.

The similar experiments have been performed for the model fire sites consisting of just certain types of FCM (needles only, leaves only or twigs only). They have indicated that the behavior of the changes of the fire extinction times depending on the FCM thickness correlates well with the dependences shown in Fig. 2a. However, it is impossible to create a stable water film on the surface of needles or twigs, unlike the model fire sites that consist of leaves only. Water covers only separate needles and twigs. Most of the water seeps into the FCM layer, almost without stopping in it. Thus, it was found out that when the diameter of the model fire site is  $d_f \approx 60$  mm and the thickness of the FCM sample is  $h_f \approx 40$  mm, the times  $t_e$  of extinguishing by individual successive droplets are: 133 s for leaves, 178 s for needles, and 192 s for twigs. If we increase the thickness of the FCM layer up to  $h_f \approx 100$  mm, we obtain the following times: 154 s for leaves, 239 s for needles, and 540 s for twigs.

The times of fire extinction by water mist  $t_e$  (with the same parameters of fire sites  $d_f \approx 60$  mm,  $h_f \approx 40$  mm) are: 103 s for leaves, 19 s for needles, and 48 s for twigs. The times  $t_e$  at  $d_f \approx 60$  mm and  $h_f \approx 100$  mm are: 115 s for leaves, 30 s for needles, and 117 s for twigs. If we increase the thickness of the material, the times  $t_e$  increase by less than 70 seconds. This is true for all types of the tested FCM. Such a result (rather small change in time  $t_e$ ) can be explained by the fact that water is irrigated uniformly over the entire FCM surface. Droplets seep into the pores of the sample. All that gives the close values of the times  $t_e$  at relatively constant rate of FCM pyrolysis through the thickness. Based



on the results obtained for water mist, we can conclude that the FCM sample thickness has weak influence onto the result of extinguishing with uniform density of irrigation. A further increase of the thickness  $h_f$  above 100 mm does not lead to any significant changes in the time  $t_e$  for all examined ways of extinguishing.

Fig. 2b illustrates the times  $t_e$  depending on the diameter  $d_f$  when the sample thickness is  $h_f \approx 40$  mm. It is evident (Fig. 2b) that when the diameter  $d_f$  increases in the range of 20–150 mm, the times  $t_e$  increases nonlinearly. Similarly to the case of the FCM thickness  $h_f$  variation, the maximal times  $t_e$  corresponds to an individual successive droplets, the minimal – to water spray. The values of  $t_e$  are also comparable for fire extinction by both water mist and the liquid film. Similar dependencies have been also obtained for the fire sites consisting only of needles, leaves or twigs. The times  $t_e$  of extinguishing of the FCM with  $d_f \approx 20$  mm and  $h_f \approx 40$  mm by individual successive droplets are: 36 s for needles, 51 s for leaves, and 50 s for twigs. The times of extinguishing  $t_e$  by the water spray are: 6 s for needles, 41 s for leaves, and 12 s for twigs.

The growth of the times  $t_e$  with increasing the diameter  $d_f$  (Fig. 2b) can be explained as follows. When  $d_f$  increases, the FCM surface area increases too. More open pores are formed, and it leads to the growth of the airflow through the FCM surface into its layer depth. It intensifies the burning of FCM. As a consequence, more water was needed and longer times  $t_e$  were spent for extinguishing the model fire site. However, as it is evident from Fig. 2b, the values of  $t_e$  saturates (the changes are small), when the diameter  $d_f$  become above 100–150 mm. In addition, it has been revealed that it is impossible to extinguish the fire site with  $d_f > 90$  mm by individual successive droplets unlike the usage of the water film or mist. This is due to the fact that the times of fire extinction and the time of total burning of the material have close values for this diameter. This feature can be explained by the fact that the rate of droplets generation by the electronic dispenser remained constant in the experiments. That is, unlike water mist, it was impossible to irrigate a large area by individual successive droplets for the same time. Consequently, the diameter of the model fire site  $d_f \approx 90$  mm can be considered as a limit when the fire extinction by individual successive droplets is not an effective because the density of irrigation of the fire site surface is not enough for its extinguishing.

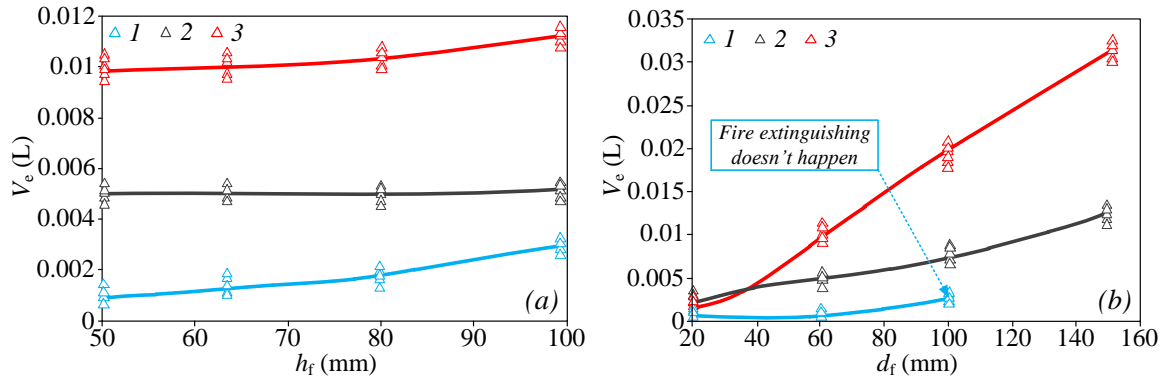
After weighting the unburned (unreacted) FCM, we found that on average, only 40–70% of the sample mass was burnt out during extinguishing of the fire sites consisting of the FCM mixture by successive droplets. The experiments with certain types of FCM indicated that the mass of the burnt sample is: 60–95% of the initial mass for the fire sites consisting of only twigs, 40–60% for needles, and 30–50% for leaves. The same parameter in the case of extinguishing of the model fire sites by water mist is: 15–30% for the FCM mixture; 20–40% for twigs, 10–35% for pine needles, and 10–25% for leaves.

It is worth to note the revealed feature of the model fire sites extinction. In the case when fire extinction starts more than 15–20 seconds later after combustion initiation, the times  $t_e$  increase for, on average, 10–15%, regardless of the method of supplying water and the characteristics of the model fire seat (diameter and height). The mass of the unburned material in this case is typically less than 30% of the initial.

An important parameter for the evaluating of the efficiency of the FCM model fire sites extinction (together with  $t_e$ ) is the amount of water spent during thermal decomposition suppression (volume  $V_e$ ). Fig. 3 illustrates the amount of water consumed for extinguishing of the model fire site depending on the thickness  $h_f$  and diameter  $d_f$  for three different mechanisms (methods) of fire



extinction. It was revealed that the smallest volume  $V_e$  corresponds to single successive droplets. The average values of  $V_e$  are observed in the experiments with the water film. The maximum volume  $V_e$  was observed at the experiments with water mist.



**Figure 3. Amount of water  $V_e$  needed for extinguishing of the FCM fire site depending on the height  $h_f$  (a) at  $d_f \approx 60$  mm and the diameter  $d_f$  (b) at  $h_f \approx 40$  mm: 1– extinguishing by individual droplets (droplet size is  $R_d \approx 1.5$  mm); 2 – extinguishing by water film; 3 – extinguishing by water mist (droplet size is  $R_d = 0.01–0.1$  mm)**

It is clear (Fig. 3a) that when the thickness  $h_f$  changes from 40 mm to 100 mm, the values of  $V_e$  grows no more than twice. When the diameter  $d_f$  of the model fire site grows from 20 mm to 150 mm, the  $V_e$  increases significantly (by 4–10 times depending on the quenching mechanism). These results can be explained as follows. The tested FCM mixture is able to keep a certain amount of water in its porous structure. When the thickness of the FCM sample increases, a portion of water, which can be absorbed (passed into the superficial reactive layer) and maintained in the material, also increases. The excess liquid seeps through the voids in the material and deposits (in the experiments, water was remained in the tray 19). However, the tested FCM are not able to accumulate a large amount of water due to their structure. As a result,  $V_e$  has small changes (Fig. 3a).

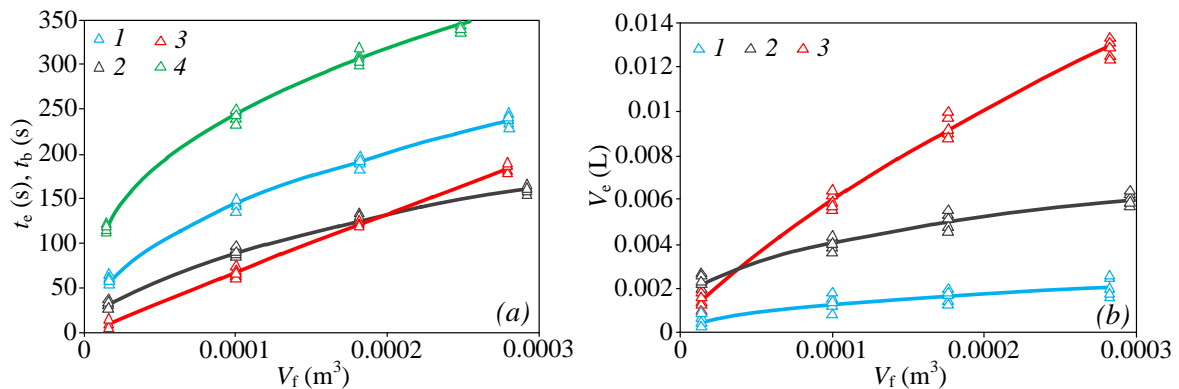
A dominant factor in determination of the volume  $V_e$  is the FCM surface area. When  $d_f$  increases (Fig. 3b), the surface area of the fire site has significant growth too. A considerably big amount of water is required to cover the entire surface area of the sample for earlier defined water volume per unit area which can be absorbed by FCM. As a result, we can notice a rapid nonlinear growth of  $V_e$  with increasing  $d_f$ . Similar dependencies are obtained for model fire sites consisting of certain types of FCM (needles only, leaves only or twigs only).

At the same time, it worth to note that together with the longest times  $t_e$  (Fig. 2), the fire extinction by individual successive droplets is characterized by consumption of smallest amount of water (Fig. 3). In contrast, the extinguishing by water mist requires the highest amount of water among all tested methods together with the shortest times  $t_e$ .

The fire extinction was essentially non-uniform in the case, when the FCM sample was allocated non-uniformly in the tray, i.e. FCM of certain type (leaves, twigs or needles) were prevailed in some parts. For example, sustainable combustion was in the places with predominant needles or twigs, while a visible extinction of flame was observed in the congestion area of leaves. Thermocouples 3 (Fig. 1) have recorded a temperature decrease in the superficial layer of leaves by 50–80 K. At the same time, the temperature did not change in the layer formed by needles and branches. This feature can be explained by properties (primarily by the shape) of the material used to

create the FCM mixture. In particular, video recordings of the experiments showed that water covers only separate needles and twigs in the areas of intensive combustion of the FCM model fire site (especially in the areas of high relative concentration of needles and twigs). Most of water seeps into the FCM layer almost without staying on its surface. Thermal decomposition penetrates to each individual twig and needle. As a consequence, substantially more water is required to reduce the FCM temperature below 370 K in such areas. Thus, it took longer time to reduce the FCM temperature at constant water supply rate. In turn, a thin water film is formed in the parts with uniform distribution of leaves (due to leaf structure). It is reflected in a noticeable temperature decrease and a slowdown of thermal decomposition of the material. However, we can conclude that in all considered cases, thermal decomposition of the FCM was terminated completely. The areas of more intensive combustion were inside the area that was characterized by oxidation slowdown. As a result, each such place was localized and the combustion there was stopped after some time. The presence of such places (areas of more intensive combustion) leads to growth of the characteristic values of  $t_e$  by 20–50 s, and  $V_e$  – within  $4 \cdot 10^{-3}$ – $9 \cdot 10^{-3}$  L. This result allows us to make an important conclusion. If ground in the forest is non-uniformly covered by FCM, then some fire sites can remain during the extinction of ground forest fire. However, these fire sites are localized within areas where the combustion virtually ceased due to the presence of a thin water film on the surface of forest litter. The thin film on the FCM surface prevents the oxidizer inflow and, as a result, prevents the further propagation of the fire from localized burning sites. This, in turn, leads to the damping or burnout of the forest fire. These results can be used as a basis for creation of the barrier strips in the localization of ground forest fire by special uniform irrigation of its burning edge until the thin water film appears on the forest cover surface.

To summarize the results, we constructed the dependencies (Fig. 4) of extinguishing times and the volumes of water spent for extinguishing with the volume of the FCM sample ( $V_f = h_f \cdot \pi \cdot (d_f/2)^2$ ,  $m^3$ ).



**Figure 4. Time of a total burnout and extinguishing (a) and amount of water (b) for extinguishing of the FCM model fire site depending on the volume of fire site: 1 – extinguishing by individual droplets (droplet size is  $R_d \approx 1.5$  mm); 2 – extinguishing by water film; 3 – extinguishing by water mist (droplet size is  $R_d = 0.01$ – $0.1$  mm); 4 – time of the FCM burnout (without extinguishing)**

Using these results (Fig. 2–4), we can make a conclusion about the possibility of usage of the one-dimensional mathematical models (for example, [5] in the theoretical analysis of the investigated processes taking into account the temperature distribution only along the thickness of the FCM layer. These results and the revealed features of extinguishing processes have to be taken into

account at prediction of the times and water consumption for the suppression of the FCM thermal decomposition. This knowledge is important for development of an appropriate mathematical models and the new techniques of localization and suppression of forest fires. In particular, the experimental database can be applied for development of the models of the FCM fire extinction under different heat transfer conditions, like described in [5, 6].

An important direction for further development of this study is an analysis of the influence of convective flows near the surface of the thermally decomposing FCM and its effect onto the fire extinguishing. Wind can have a decisive influence at different conditions of heat transfer on the FCM surface. It is advisable to study the influence of side-wind, counter- and fair-wind onto the time of suppression of the FCM thermal decomposition. The references [12] make it clear that wind effect is an independent and very complicated problem at the investigations of issues of the extinguishing processes optimization.

#### 4. Conclusion

The experiments show that it is possible to extinguish FCM by a drip flow, water mist or even a thin liquid film (in the case of pulsed water supply). The choice of the way of extinguishing depends on the priority: whether minimum water consumption or minimum time of the combustion suppression. Water mist (aerosol flow with droplets of less than 100  $\mu\text{m}$  in size) is characterized by minimum times of extinguishing. It is also possible to suppress the FCM model fire sites by successive individual rather large droplets (about 3 mm in diameter). In this case, the time of extinguishing is maximal from all the experiments. If the combustion area is ten or more times greater than the surface area of generated droplets, extinguishing is not possible.

The integral characteristics of observed processes indicate the relevance of usage of the one-dimensional formulations (in particular, the approach proposed in studies [5] in numerical simulation of heat and mass transfer under the conditions of the FCM thermal decomposition suppression. Recall that we have obtained the integral characteristics by varying the diameter and height of the FCM model fire site. As a consequence, we can conclude that it is reasonable to use one-dimensional models taking into account heat and mass transfer through the thickness of FCM.

#### Acknowledgement

The investigation of interaction between FCM and water droplets was supported by the Russian Science Foundation (14–39–00003). The features of extinguishing were investigated at the support by the Grant of President of Russian Federation (MD–1221.2017.8).

#### Nomenclature

$d_f$  – diameter of cylinder with FCM sample [mm]

$h_f$  – height of cylinder with FCM sample [mm]

$m_{f0}$ ,  $m_{fd}$ ,  $m_{fw}$  – initial mass of FCM sample, before and after thermal drying [g]

$n$  – number of droplets needed for extinguishing

$R_d$  – radius of water droplets [mm]

$S_f$  – surface area of FCM [ $\text{m}^2$ ]

$t_b$  – time of total combustion (FCM thermal decomposition) of model fire site [s]

$t_e$  – time of the model fire site extinction [s]

$T_f$  – temperature in FCM layer [K]

$U_d$  – velocity of droplet [m/s]  
 $V_d$  – volume of individual droplet [L]  
 $V_e$  – amount of water needed for model fire site extinction [L]  
 $V_f$  – volume of cylinder with FCM sample [m<sup>3</sup>]  
 $V_s$  – amount of water remaining in tray after the extinguishing [L]  
 $\gamma_f$  – wetness of the FCM [%]  
 $\mu_w$  – specific consumption of water by spray nozzle [L/s]  
 $\rho_f$  – density of the FCM in sample [kg/m<sup>3</sup>]

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