FEATURES OF PROPAGATION OF DROPLETS OF WATER AND SPECIAL WATER-BASED COMPOSITIONS IN A SAMPLE OF FOREST FUEL MATERIAL

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The article presents the results of experimental studies of water droplets propagation through the sample of typical forest fuel materials: needles, leaves, and their mixture. Different conditions are considered: without any additional energy supply, with heating, in the course of intensive thermal decomposition and flaming combustion. Three methods of registration are applied: thermocouple measurements; control of the weight of the sample as a whole and of its individual layers; and high-speed video recording. Water-based compositions with special additives (bentonite, bischofite, and foaming agents) typical for forest fire extinguishing systems are used. The experiments are carried out using aerosol and single water drops, as well as a small group of the latter. It is shown that the mechanisms, conditions and characteristics of droplet propagation through the layers of needles, leaves and their mixtures differ significantly. The scientific novelty of the work is the determining of the values of all the key characteristics of these processes in the conditions of intensive pyrolysis of the material, as well as through its inert layers.

Key words: *forest fuel material; pyrolysis; localization; protective water line; liquid propagation; water retention in deep layers; liquid distribution in forest fuel material.*

1. Introduction

The effective use of water or other composition on its basis in the suppression of combustion of various materials plays a decisive role in the conditions of significant restrictions on the simultaneously supplied volumes of the latter [1–3]. Usually small number of aircraft is involved in the suppression of forest burning [4–6]. The air fleets of many countries often have few aircraft [4, 5]. As a result, the problem of rational consumption of water or special compositions on its basis in in the combustion zone is topical [7].

In recent years, experiments and bench tests have been carried out to formulate conclusions about the appropriateness of time and space distributed water supply to the combustion zone for the localization and complete suppression of combustion [8]. It is shown that effective (in terms of time of localization and volume of water) conditions can be ensured by specialized systems of droplet aerosol puffing [7, 8]. At that it is important to ensure the completeness of water evaporation in the flame burning zone, as well as to cover the free surface of the pyrolyzing material.

In the early works (in particular, [7–12]) the authors have shown results of experimental and theoretical research of suppression of burning of typical forest fuel materials of drops, films, aerosols, unsprayed water arrays (including with the use of specialized fire extinguishing additives). The main focus of the research during 2014–2016 was on the creation of technology for extinguishing forest fires by droplet flows, distributed in time and space. Such flows can be created with specialized polydisperse spraying of water into the combustion zone from different heights relative to the surface of the forest. It has been found [7–12] that effective conditions for localizing the forest material combustion become possible with temperature decrease in the gas phase above the material surface as well as with blocking the oxidizer access to the combustion zone and the outflow of thermal decomposition products from the sample material into the gas phase. These conditions may be fulfilled by controlling the completeness of evaporation of the extinguishing liquid in the gas phase and on the surface of the pyrolyzing material. For example, in [7] the results of experimental studies show the limiting concentrations and sizes of liquid droplets, at which it is possible to ensure their complete evaporation in the flow of high-temperature combustion products. Such data served as a basis for the creation of a group of models [8] for the suppression of combustion and pyrolysis of forest materials at their contact with liquid droplets and films, as well as aerosol and vapor clouds. In experiments [7] and in modeling [8], important regularities of droplet entrainment from the combustion region by high-temperature combustion products have been established. This factor prevented the complete evaporation of the liquid in the combustion zone. Accordingly, the proportion of fluid involved in endothermic transformations decreased. It was advisable to establish reliable connections between the main parameters of the flow of combustion products, the combustion region and the extinguishing fluid. In [9,10] results of experiments on registration of these connections with use of a hardware-software complex on the basis of low-inertia thermocouples and panoramic optical methods are given, the limiting sizes, concentrations and speeds of movement of drops at which it is possible to provide their movement in high-temperature streams of products of combustion opposite in the direction and effective suppression of burning are shown. The average size and concentration of droplets reaching the surface of pyrolyzing materials are predicted using data [9,10]. These data were used in experiments [11,12] to establish the characteristics of combustion localization. According to the results of studies [7-12], it was concluded that the optimal consumption of fire extinguishing fluid in the combustion zone with the provision of conditions for complete suppression of pyrolysis of forest materials in real practice is possible with the use of a group (at least 5-8) of aircraft and helicopters, simultaneously carrying at least 30-50 tons of liquid. Ensuring such conditions for many of the emergency services difficult. Therefore, the rational stage of development the results of research [7-12] has been the development of theories on the creation of effective protective strips that prevent the spread of fronts of pyrolysis and combustion. These stripes can be generated when the moisture of forest litter. As a consequence, it is important to carry out the processes of promotion of typical fire extinguishing liquids through the layers of typical forest combustible materials. The results of experiments with water are given in [13]. It is advisable to develop this work on the most typical fire-extinguishing compositions with specialized additives.

This factor prevented the complete evaporation of the liquid in the combustion zone. Accordingly, the proportion of fluid involved in endothermic transformations decreased. It was advisable to establish reliable relations between the main parameters of the flow of combustion products, the combustion region and the extinguishing fluid. Works [9,10] present the results of experiments on registration of these relations using a hardware-software complex on the basis of low-inertia thermocouples and panoramic optical methods, and show the limiting sizes, concentrations and speeds of droplets motion at which it is possible to provide their motion in opposite high-temperature flows of combustion products and effective suppression of burning. The average size and concentration of droplets reaching the surface of pyrolyzing materials have been predicted using data of [9,10]. These data were used in experiments of [11,12] to establish the characteristics of combustion localization. According to the results of [7–12], it has been concluded that the optimal consumption of fire extinguishing fluid in the combustion zone with complete suppression of pyrolysis of forest materials in real practice is possible with the use of a group (at least 5–8) aircraft and helicopters, simultaneously carrying at least 30–50 tons of liquid. Ensuring such conditions is difficult for many of the emergency services. Therefore, the rational stage of development of research results [7–12] has been the elaboration of the theory of effective protective lines that prevent the spread of the fronts of pyrolysis and combustion. These lines can be made at moistening the forest litter. Hence, the propagation of typical fire extinguishing liquids through the layers of typical forest fuel materials is important. The results of experiments with water are given in [13]. Further studies should deal with the most typical fire-extinguishing compositions with specialized additives.

The least experimentally studied of all significant factors, effects and processes occurring under these conditions, is water droplets propagation through the FFM (Forest Fuel Material) sample [13]. In this case, thermal decomposition of the material can have a significant impact on the movement of droplets between the FFM layers [14–19]. This is due to the need to use low-inertia thermocouples, high-speed cameras and software systems with tracking algorithms. The results of the first experiments in this field [13] have shown that it is advisable not only to study the features of water droplets propagation through the layer of forest fuel material, but also to establish the peculiarities of their retention in the porous structure of FFM and evaporation throughout their lifetime.

The purpose of this work is an experimental study of the characteristics of propagation of droplets of water and specialized compositions on its basis through the forest fuel material using high-speed video recording, low-inertia thermocouples and sample weight control.

2. Experimental Setups and Methods

2.1. Materials

A hollow cylinder (inner diameter $d \approx 0.1$ m and height $h \approx 0.12$ m) filled with forest fuel material was used to create model beds of a ground forest fire. Three types of FFM were considered: pine needles, birch leaves, and mixture of materials. To determine the moisture content of the FFM sample, the latter was pre-dried for 3–5 days at a temperature of about 25 [°C]. Right before the cycle of experiments, the moisture of the material was determined (by thermal drying). For these purposes, the studied FFM was weighed on the scales and then placed in a drying furnace at a temperature of about 100 [°C] for 2–3 hours. After drying, the sample was cooled and re-weighed. ViBRA HT 84RCE scales were used. The influence of special additives to water: foaming agent (volumetric concentration of 0.3%), bischofite (mass concentration of 8%) and bentonite (mass concentration 5%) on the characteristics of the process was also studied in the experiments.

2.2. Experimental Setup and Procedure

When analyzing the features of experiments [13], it can be concluded that in order to achieve the goal of this study, it is advisable to use two schemes for registering the rates of droplet motion through the layers of the sample material: by controlling the readings of thermocouples located at different heights in the sample; and with the use of high-speed video recording. However, due to the pyrolysis, water evaporation is intensified. In such circumstances, video recording is difficult. Therefore, the second approach is based on the control of the sample weight.

The stand was used for experimental studies of the laws of motion of droplets of water and special compositions on its basis through the near-surface and deep layers of FFM with different approaches to spraying under intense thermal decomposition, as well as in the periods preceding these processes. Experimental registration of the aerosol drops motion in the FFM layer up to their full brake was carried out in two stages. The sample thickness h_f≈0.04 m, the surface area S_f≈0.00785 m^2, and the density of the sample material ρ_f≈17.24 kg/m^3. Two types of nozzle devices with dimensions of drops: R_{dsp}=0.01–0.12 mm and R_{dsp}=0.1–0.25 mm, were used. At the first stage, the FFM sample was weighed on the laboratory scale (Fig. 1,*a*). The initial weight of the FFM sample was taken as zero. The sample was located between the two nozzles. During a certain time interval (t_{sp}≈5 s; t_{sp}≈10 s; t_{sp}≈20 s; t_{sp}≈30 s) an aerosol flow was generated. For each stage, the mass of water retained in FFM for 120 seconds (t) was recorded. Experiments of the second phase were conducted in a continuous flow of liquid aerosol with the dispersion of drops R_{dsp}=0.01–0.12 mm. The FFM sample was placed under the nozzle device, and the volume of water retained in the FFM (V_{fm}), as well as the volume of water passing through the layer (V_{ofm}) was recorded every 5 seconds. The ranges of initial parameters are chosen to clearly demonstrate the differences in the propagation of liquid droplets through the layers of forest fuel materials with different sizes and backfill density.

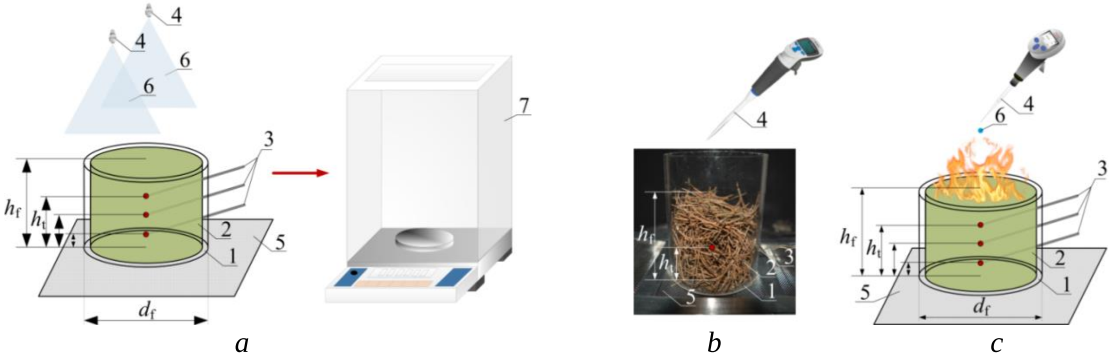


Fig. 1. Conventional scheme of experiments (without pyrolysis of FFM) under the influence of liquid aerosol (*a*) (1 – hollow cylinder with FFM sample; 2 – FFM; 3 – low-inertia thermocouples; 4 – spraying nozzle; 5 – grid (1×1 mm); 6 – aerosol, 7 – laboratory scales) and single drops (*b*, *c*) (model bed (*b* - sample in the initial state (not subjected to pyrolysis), *c* – FFM is thermally decomposing): 1 – hollow cylinder with FFM sample; 2 – FFM sample; 3 – low-inertia thermocouples; 4 – single-channel dispenser; 5 – grid (1×1 mm); 6 – drop of liquid)

Experiments with single drops were carried out in two stages (Fig. 1,*b*,*c*). At the first one, water drops were placed on the surface of the FFM sample, not subjected to pyrolysis. The second stage involved identical experiments with thermally decomposing FFM. In this case, the initiation of thermal decomposition of FFM was realized with the use of three piezo-ignition devices. The latter ignited FFM in the upper part of the sample. Then it was necessary to wait for 15-20 seconds, until the temperature in the layer of FFM throughout the thickness exceeded the temperature of the beginning of thermal decomposition – 130 [°C].

Density and moisture of FFM sample were selected as average values relative to virtually possible for forest fires. In particular, the density ρ_f was 18 [kg·m^{-3}] (calculated by the formula

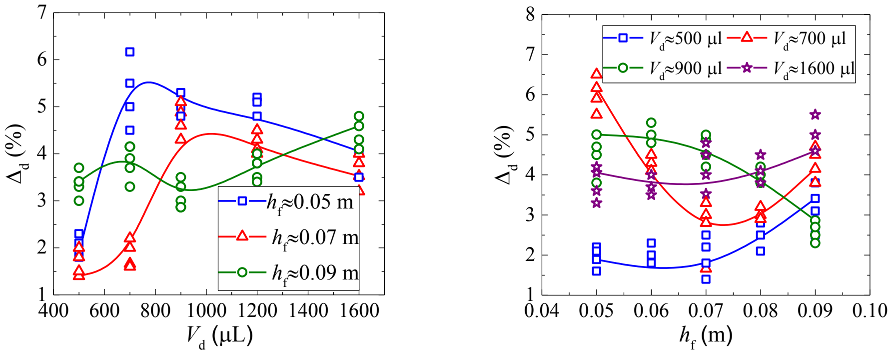
$\rho_f=m_{f0}/(h_f\cdot S_f)$, [kg·m^{-3}], where $S_f=\pi\cdot(d_f/2)^2$, [mm^2], and the relative moisture was 7–10% (calculated by the formula: $\gamma_f=(m_{fw}-m_{fd})/m_{fw}\cdot 100$, %. The minimum density of the sample serves to identify the effect of the properties of the extinguishing liquid on the physical and chemical processes, occurring in the suppression of combustion and thermal decomposition of FFM. Besides, studies of the considered processes under conditions without combustion of FFM were focused on the influence of additives to water on the conditions of its movement through the layers of FFM.

Systematic errors in determining the recorded parameters are described below. The sample weight of FF and water was determined using the laboratory microbalances with a precision of 10^{-5} [g]. The mass concentration of bentonite and bischofite impurities in water was also controlled by microbalances, and the error did not exceed 0.01%. The volume concentration of foaming agents in water was determined by the error of the electronic microdoser and did not exceed 0.1%. The temperature in the FFM layer was recorded by low-inertia (type K) thermocouples with an accuracy of 1.5 [°C] and a thermal delay time of no more than 0.5 [s]. Measurement of droplet sizes was carried out using the Shadow Photography method with the systematic error of 0.002 [mm].

3. Results and Discussion

3.1. Comparing the characteristics of motion of large droplets and fine aerosol elements through the material sample.

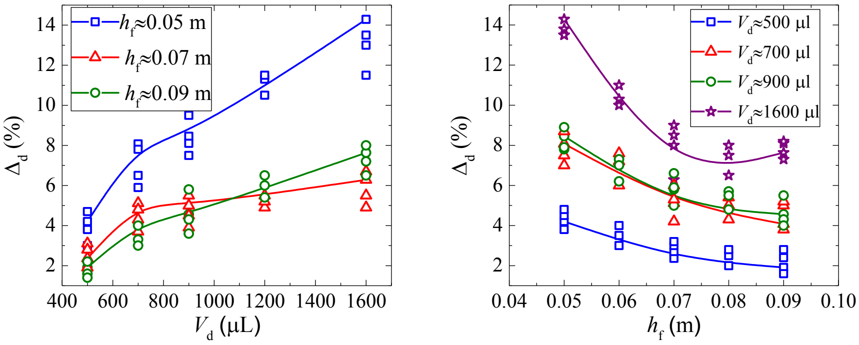
One of the most significant factors determining the efficiency of FFM combustion suppression is the characteristic droplet size used to extinguish forest fires [7–9]. For this reason, one of the important tasks of the study was to compare the characteristics of propagation of large and small water droplets through the FFM sample. Fig. 2 shows the dependences of these characteristics at water droplets propagation through a layer of needles (without pyrolysis) on different FFM thicknesses.



a *b*

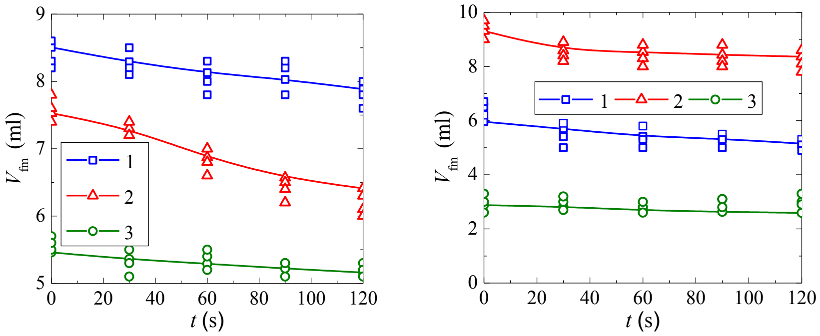
Fig. 2. Dependences of Δ_d on the total volume of water droplets (*a*) and the thickness of the FFM sample (needles) (*b*) in the absence of pyrolysis (at room temperature)

Fig. 3 shows the dependences at water droplets propagation through a layer of FFM, subjected to thermal decomposition, and Fig. 4 presents the results of monitoring the water volume passing through the samples of leaves, needles and a mixture of materials. Analysis of dependences given in Figs. 3, 4 allows concluding that the volume of water that entered in the FFM practically does not come out of the sample material over time. It is seen in Fig. 4 that the propagation of water volume in the layer of leaves is 14% for 120 [s] compared with the volume in the initial time. When spraying aerosol (Fig. 5) with a characteristic droplet size R_{dsp}=0.1–0.25 mm there is reduction of the retained water volume in a layer of needles and FFM mixture by 9% and 14%, respectively. Fig. 5 demonstrates how the values of water volume in the FFM sample increased over time with the continuous supply of liquid aerosol. Almost linear dependences illustrate the dominant value of the retention of water, supplied to the sample, in its layers.



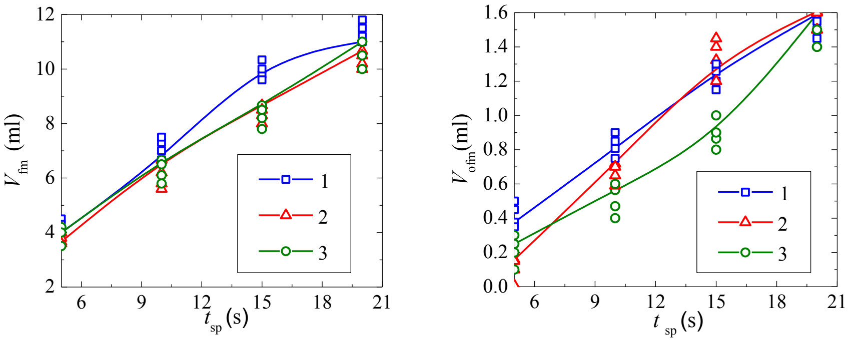
a *b*

Fig. 3. Dependences of Δ_d on the volume of water droplets (*a*) and the thickness of the sample (*b*) under conditions of propagation through the layer of FFM (needles) exposed to pyrolysis



a *b*

Fig. 4. Dependence of the water volume retained in FFM at *h_f*≈0.04 m (*t_{sp}*≈30 s) (*V_{fm}*) on time (*a* – *R_{dsp}*=0.01–0.12 mm; *b* – *R_{dsp}*=0.1–0.25 mm): 1 – needles, 2 – leaves, 3 – mixture of FFM

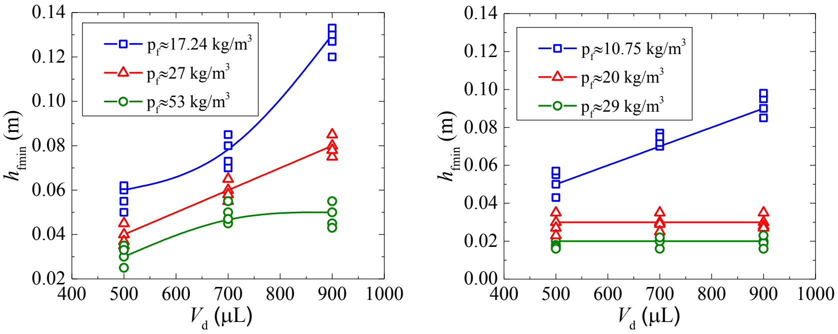


a *b*

Fig. 5. Dependences of the water volume retained and supplied to the catcher on time under conditions of continuous supply of liquid aerosol with *R_{dsp}*=0.01–0.12 mm (a - retained in FFM *h_f*≈0.04 m; b - in the catcher (i.e. passed through the sample): 1 – needles, 2 – leaves, 3 – mixture of FFM

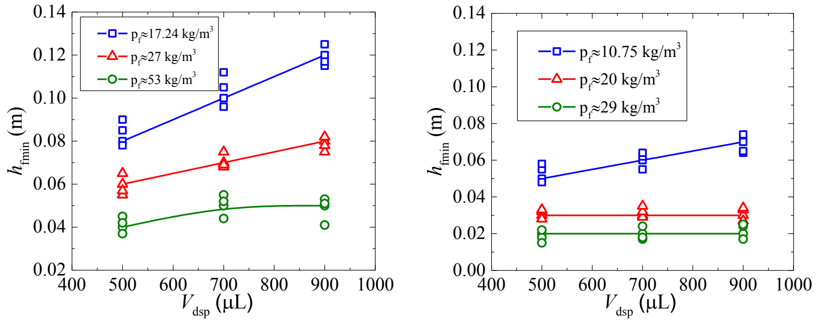
3.2. The effect of filling density on moisture retention in the layers of FFM

The experiments were carried out in two stages. The first was to record the minimum thickness of the layer h_{fmin}, where a drop of water is fully retained (stops) (Fig. 6,*a*). The second was to determine the area (layer) of FFM, where the same volume of water but sprayed by the nozzle device is retained (Fig. 6,*b*). The surface area $S_f \approx 0.00785$ m^2. Studies were carried out under typical conditions for modern aerosol systems of fire extinguishing: droplet size of 0.01–0.12 [mm], irrigation density of 0.014–0.016 [$\text{l}\cdot\text{m}^{-1}\text{s}^{-1}$], and water flow of 0.7 ml/s. The used droplets with initial volumes had the following radii: $V_d \approx 500$ μl – $R_d \approx 4.9$ mm; $V_d \approx 700$ μl – $R_d \approx 5.5$ mm; $V_d \approx 900$ μl – $R_d \approx 5.9$ mm. The results of the experiments are shown in Figs. 6, 7.



a *b*

Fig. 6. Dependences of the minimum thickness of the FFM sample, through which a single drop of water does not permeate, on its initial volume at different density of filling (*a* – needles; *b* – birch leaves)



a *b*

Fig. 7. Values of the minimum thickness of the FFM sample, through which a fixed volume of water does not permeate if sprayed through the nozzle device (R_{dsp}=0.01-0.12 mm) under conditions of different filling density (*a* – needles; *b* – birch leaves)

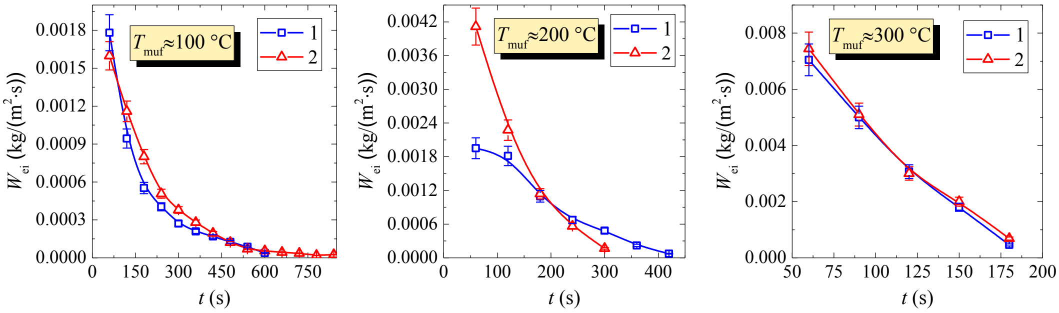
Analysis of dependences given in Figs. 6, 7 allows concluding that for water volumes of 500 [μl], a decrease in the limit thickness h_{fmin} of the layer of needles is noticeable when the volume is generated in the form of a single drop. The established effect is most likely associated with the structure of the sample and the properties of the needles, namely with their geometric dimensions (the length of the needles is 0.06–0.08 [m]). Since the diameter of the model bed $d \approx 0.1$ m, then, at stacking over the cylinder perimeter the sample has higher density in the central part than in the periphery of the model bed. During the experiments, water droplets were generated directly into the centre of the bed. The established results correspond to the main physical processes and, as a consequence, do not require a detailed explanation.

3.3. Evaporation of moisture in FFM layers with different filling density

Experiments were also carried out to analyze the evaporation rates of water in the porous structure of FFM at sample heating in the muffle furnace. The experimental technique included the following sequential procedures:

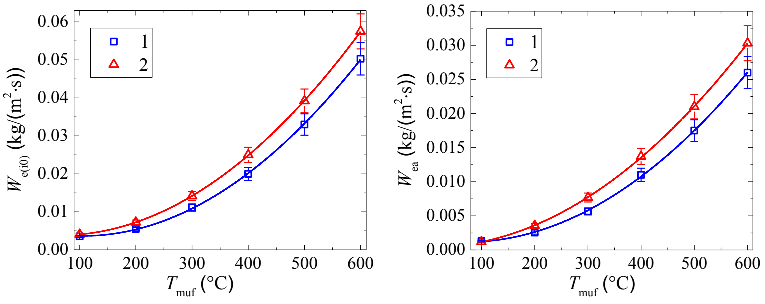
- the hollow aluminum cylinder (diameter d_f≈60 mm, height h_f ≈50 mm) was filled with FFM;
- the required air temperature in the muffle furnace was set (the electric furnace EKPS-10 with temperature range of 50–1100 [°C], error of ±1 [°C], and chamber volume of 10 [l]). The air temperature in the furnace in the experiments was T_{muf}=100–300 °C;
- using laboratory microscales, the weight of the FFM sample was recorded (the weight of the FFM sample was m_f=2.6–2.8 g, and the bulk density of the sample ρ_f≈19 kg/m^3);
- the FFM sample was wetted with water using a spraying nozzle, generating water aerosol (droplet size R_d=0.01–0.12 mm);
- using microscales, the weight of the FFM sample with water $m_{f\text{-}w}$ was determined. The mass of water in the FFM layer in the experiments was m_w =1.6–1.9 g;
- the substrate with FFM sample was placed inside the muffle furnace;
- with step in time Δt=60 s, the mass of FFM with water ($m_{f\text{-}w}$) was recorded. The measurements continued until complete evaporation of water from the layer of FFM, i.e., until compliance with the condition of $m_{f\text{-}w}$≈m_f.

The instantaneous (W_{ei}) and average (W_{ea}) mass rates of water evaporation from the surface of FFM were determined by the results of experiments (similar to experiments with local heating). Figs. 8, 9 demonstrate the results of experimental studies.



A *b* *c*

Fig. 8. Maximum mass evaporation rates (W_{ei}) of water from the interstitial surface of FFM (ρ_f≈19 kg/m^3): *a* – T_{muf}≈100 °C; *b* – T_{muf}≈200 °C; *c* – T_{muf}≈300 °C (1 – needles; 2 – leaves)



a *b*

Fig. 9. Dependences of the maximum mass evaporation rates ($W_{ei(0)}$) of water at the initial time (*a*), as well as the average mass evaporation rates (W_{ea}) for the entire period of time (*b*) on the average air temperature in the furnace (T_{muf}) (ρ_f≈19 kg/m^3): 1 – needles; 2 – leaves

The rate of water evaporation from the leaves' surface exceeds the same values of this parameter for needles. With an increase in ambient temperature up to 600 [°C] the difference is about 25%. This result can be explained by the fact that in the case of needles, the liquid is distributed evenly throughout the volume of the sample, and in the case of leaves most of the water deposits the upper part of the sample. Thus, the water on the surface evaporates many times faster than that retained in the FFM layer.

3.4. Changes in the structure and density of the filling material under the action of water

Experiments were carried out with the model bed (h_f≈0.04 m, S_f≈0.00785 m^2) under the conditions of liquid aerosol generation (R_{dsp}=0.01–0.12 mm). The minimum volumes of water that are retained in the layer and do not pass through it (dependences 1, 3 in Fig. 10) have been determined. Experimental dependences (curves 2 and 4 in Fig. 10) determining the minimum volume of water, sufficient to prevent fire propagation through the wetted barrier line created in advance have been determined as well (according to the method [20]). The most valuable are not only the quantitative research results, but also the type of curves in Fig. 10. The reason is that it reflects the physical characteristics of the processes in the system, in particular, the processes of water accumulation in the layers of the sample and deceleration of their propagation, intensification of evaporation during pyrolysis, as well as significantly heterogeneous distribution in the material samples due to their different structure.

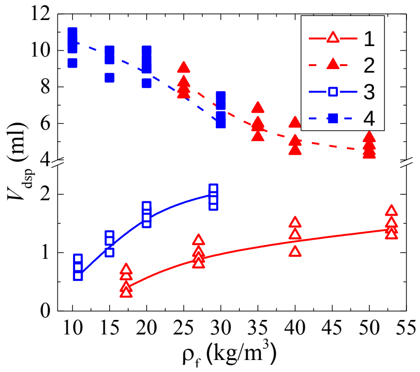
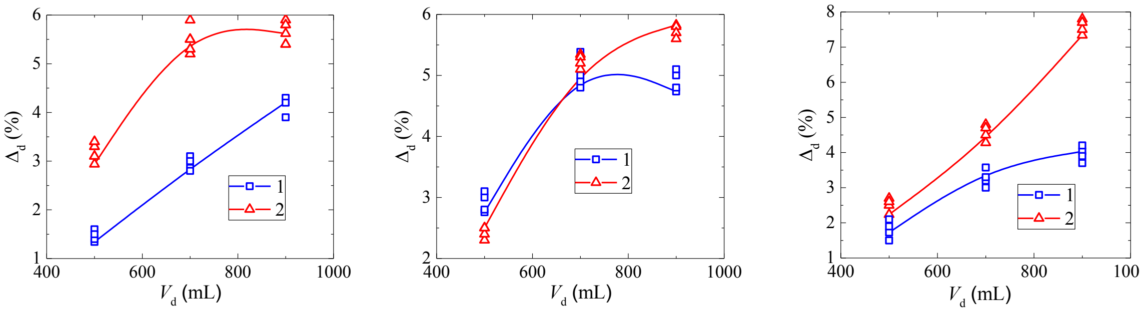


Fig. 10. Dependences of the minimum volume of water that is completely retained in the FFM layer on the bulk density of the material: 1 – needles (h_f≈0.04 m, S_f≈0.00785m^2); 2 – needles (protective line); 3 – leaves (h_f≈0.04 m, S_f≈0.00785m^2); 4 – leaves (protective line)

3.5. Comparison of water and special compositions on its basis

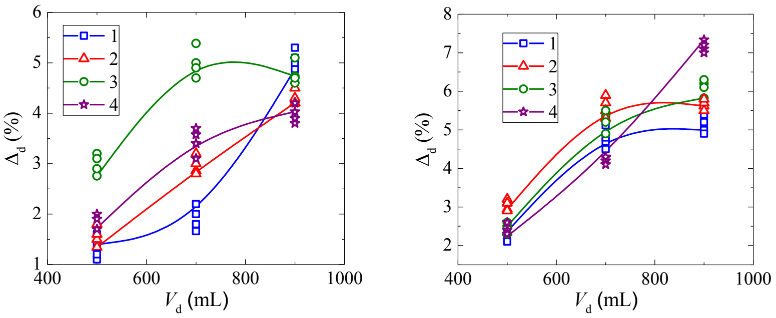
The main mechanisms and macroscopic regularities of FFM extinction by water-based compositions with the addition of typical impurities have been identified (Figs. 11, 12). Analysis of dependences given in Figs. 11, 12 allows concluding that specialized chemical additives to water significantly affect the conditions of drops propagation through the layers of FFM. In particular, it may be seen that the composition with added foaming agent is retained in the needles layer in a much larger volume compared to other additives. The established effect is explained by the fact that such additives reduce the surface tension of water, and when contacting the needles the drop is divided into smaller parts, there by enveloping the largest area of the material. In addition, in studies with combustion of the FFM sample it was registered that the flame height significantly decreases during the passage of a drop with added foaming agent.

The additive of fire-retarding “bentonite” on the contrary increases the surface tension of the liquid composition. Fig. 12 shows that when generating droplets with a volume of 900 [μl], almost the entire volume is retained in the FFM layer. One of the key mechanisms of fire localization is implemented in the conditions of fire extinguishing using a fire-retarding “bentonite”. The release of products of thermal decomposition of FFM is blocked. When adding the fire-retarding agent “bischofite” into water, there is an effective retention of the droplets compared to pure water. Thermophysical characteristics of the composition with added bischofite differ significantly from those of water [21, 22]. In Fig. 12 it may be also seen that there is a need in a larger energy to heat up the composition, hence the values of Δ_d have increased.



a *b* *c*

Fig. 11. Dependences of Δ_d on the volume of droplets with additive ((*a*) – bischofite, (*b*) – foaming agent, (*c*) – bentonite) on the volume of droplets at $h_f \approx 0.07$ m (needles): 1 – without pyrolysis; 2 – with pyrolysis



a *b*

Fig. 12. Dependence of Δ_d on the volume of droplets of extinguishing liquid passing through the layer h_f≈0.07 m (needles): *a* – without pyrolysis; *b* - with pyrolysis (1 – water; 2 – bischofite; 3 – foaming agent; 4 – bentonite)

4. Conclusions

(i) The conducted experiments served to create an information database with the values of the main characteristics of water droplet propagation through the sample of typical forest fuel materials. The most valuable parameters are the rates and depths of water motion at different density of material filling, its type and structure. Important experimental information has been also obtained on the ranges of water evaporation rates in the FFM samples. This information is the basis for the development of reliable predictive models of water evaporation from porous materials with complex structure.

(ii) The results of the experiments and their analysis are important for the development of science and technology in the field of interaction of droplet aerosols and highly porous materials. The sphere of application of the results is extremely wide: irrigating materials with liquid and other compositions; localizing and extinguishing fires; higher density or special filling of the pores of the materials, etc. Experimental information serves as a basis for the development of appropriate physical and mathematical models.

Acknowledgments

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Nomenclature

d – diameter of hollow cylinder, [m]
h – height of hollow cylinder, [m]
h_f – height of the FFM sample, [m]
h_{fmin} – maximum height of the FFM sample, where a fixed amount of fluid deposits, [m]
m_f – FFM sample weight, [kg]
m_{f0} – mass of FFM, [kg]
m_{fd} – mass of FFM after thermal drying, [kg]
m_{fw} – mass of FFM prior to thermal drying, [kg]
$m_{f\text{-}w}$ – weight of FFM sample with water, [kg]
m_w – water mass, [kg]
R_d – droplet size, [mm]
R_{dsp} – radius of droplets in aerosol flow, [mm]

S_f – surface area of the FFM sample, [m^2]
t – time, [s]
t_{sp} – time of aerosol flow spraying, [s]
T_{muf} – air temperature inside the furnace, [°C]
V_d – initial volume of a single droplet, [μl]
V_{fm} – volume of water “deposited” in the FFM layer over time, [ml]
V_{ofm} – volume of water “permeated” through the FFM layer over time, [ml]
W_{ea} – mass-average evaporation rate of water from the surface of FFM, [kg/(m^{2}s)]
W_{ei} – instantaneous mass evaporation rate of water from the surface of FFM, [kg/(m^{2}s)]
Δ_d – relative mass of liquid droplets retained in the FFM layer, [%]
γ_f – relative moisture of the FFM sample, [%]
ρ_f – density of the FFM sample, [kg/m^3]

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