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INTERACTION OF A LIQUID AEROSOL WITH THE COMBUSTION FRONT OF A FOREST COMBUSTIBLE MATERIAL UNDER THE CONDITIONS OF COUNTERCURRENT AIR FLOW

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Experimental investigations on the characteristic times of suppression of the flame combustion and thermal decomposition of wastes of coniferous and deciduous forest trees under the action of a liquid aerosol have been performed. As forest combustible materials, birch leaves and a mixture of components of a forest ground cover (leaves, needles, twigs) were used. Three schemes of interaction of a water droplet flow with a forest combustible material in the process of its burning were considered: the first scheme in which a material is preliminary moistened by the water sprayed upstream of its combustion front, the second scheme in which a liquid aerosol is supplied directly to the combustion front, and the third combined scheme in which water is sprayed upstream of the combustion front and over it. The influence of a favoring and an adverse air flows on the termination of combustion of a model fire hotbed was investigated. The conditions of spraying of water over forest combustible materials, providing the suppression of their flame combustion and thermal decomposition, were determined.

Keywords: *forest combustible material, flame combustion, thermal decomposition, combustion front, aerosol flow.*

Introduction. The localization and liquidation of forest fires has been an important and, at the same time, very complex problem for the entire world community for years [1–5]. The extinguishing of fires in large areas of a boreal big stand is carried out as a rule with the use of aircraft [6, 7]. To date a local throw-down of an extinguishing liquid to a big-stand region limited in its characteristic sizes has been used traditionally. The experience of many years on the use of aircraft for the suppression of forest fires does not allow one to conclude that this method of fire extinguishing is effective [8–11], which is explained first of all by the absence of techniques for the special spraying of water with its distribution with space and time in a fire zone. The use of an increased number of flying vehicles for the suppression of a forest fire does not solve the problem of effective fire extinguishing because the weather conditions influence this process [3]. The prediction of the occurrence and spread of a forest fire is also an important component of its fighting [12–15]. The velocity of an air flow does not exceed 3 m/s under conditions typical for practice, but often this velocity increases to 10–20 m/s. It is known that a wind load on a forest fire intensifies the flame combustion of a forest combustible material (FCM). Moreover, as experiments show, a wind can substantially influence the physicochemical processes occurring in a FCM under the conditions of suppression of its flame combustion and thermal decomposition [16]. Of interest are experimental investigations on determination of the influence of a wind, favorable or adverse in relation to the direction of movement of a forest fire, on the termination of the flame combustion and thermal decomposition of forest combustible materials.

The aim of the present work is experimental investigation of the conditions and characteristics of the suppression of the flame combustion and thermal decomposition of a FCM, experiencing an air flow opposite in direction to the direction of movement of the fire, by different schemes of action of a liquid aerosol on the FCM.

Experimental Stand and Investigation Methods. In the experiments, we used samples of birch leaves and a tree waste representing a mixture of birch leaves (25%), pine needles (15%), and twigs of deciduous and coniferous trees (60%). The choice of these forest combustible materials is explained by the fact that it is precisely the tree waste of a boreal forest that ignites first under the conditions of forest fire, and in the territory of Russia there are a large number of deciduous plantations [17]. The weight of a FCM sample was 50 g. As a model fire hotbed, a metal pan of length 310 mm, width 195 mm, and depth 45 mm was used. The investigations on determination of the times of suppression of the flame combustion

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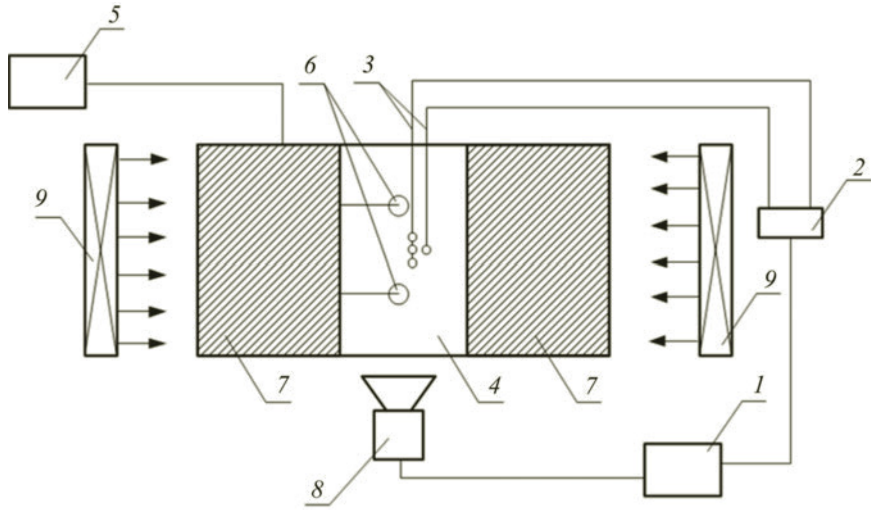

Fig. 1. Diagram of the experimental stand: 1) working station; 2) digital thermometer; 3) thermocouples; 4) pan with a FCM; 5) vessel with water; 6) sprayers; 7) vessel for water; 8) high-speed video camera; 9) air blowers.

and thermal decomposition of a FCM experiencing an air flow opposite in direction to the direction of movement of the combustion front were performed on an experimental stand whose diagram is shown in Fig. 1. A liquid aerosol with droplets of radius $R_d \approx 0.01$–0.12 mm was generated by two sprayers 1 with a spray-cone angle of ~30^o, fixed at a height of ~400 mm above a model fire hotbed. The distance between the sprayers was ~100 mm. The pressure in the channel through which water was supplied to the sprayers was $P = 2.5$ atm.

Unlike the experimental investigations performed in [18], the suppression of the flame combustion and thermal decomposition of a FCM was realized under the conditions where the FCM experienced an air flow favorable or adverse relative to the direction of movement of a fire. In the experiments, three schemes of action of a liquid aerosol on a FCM subjected to thermal decomposition were used. In accordance with the first scheme (Fig. 2a), a water droplet flow of transverse size L was formed in advance under the conditions where blower 7 was activated, and this flow humidified a region of a FCM. Then the FCM was fired with the use of three piezoelectric burners at a time for provision of its uniform combustion across metal pan in which it was positioned, and blower 7 caused the combustion front of the FCM to move in the direction to the FCM region humidified by water droplets. Once the combustion front reached the fire edge formed in advance, blower 7 was deactivated and blower 8 was activated. As a condition of termination of the flame combustion and thermal decomposition of a FCM, decay of these processes within the FCM region acted upon by the liquid aerosol was considered. Moreover, we controlled the fulfillment of the condition of decreasing the temperature of a FCM T_{FCM} in its thickness to a level lower than the temperature (~370 K) at which the thermal decomposition of the FCM begins, with the use of thermoelectric transducers 3. In accordance with the second scheme, water was supplied directly to the front of combustion of a FCM (Fig. 2b), whose movement on the surface of the FCM was controlled using a high-speed video recording camera. A water droplet flow was generated at the instant a flame reached the central region ($L/2$) of the water screen formed in advance. Then blower 8 was activated and blower 7 was deactivated. The third scheme can be considered as a combined scheme with respect to the method of water spraying. In the case where this scheme was used, water was sprayed upstream of the front of combustion of a FCM and over this front at a time (Fig. 2c), and a liquid aerosol was supplied to the FCM under the conditions where blower 8 was activated and blower 7 was deactivated at the instant a flame reached the front edge of the zone of preliminary action of a water droplet flow on the FCM on the side of movement of the combustion front.

Prior to the main experimental investigations, we performed experiments on determination of the specific density ζ_{FCM} of the water sprayed over a FCM with the use of the method proposed in [19, 20], and ζ_{FCM} was estimated on average at approximately 0.0375 L/(m^2·s). The times of termination of the flame combustion and thermal decomposition of a FCM t_f and $t_{t.d}$ and the minimum time of spraying of water over the FCM t_{min} were determined with an error of 0.5 s. The maximum random errors in determining the temperature T_{FCM} of a FCM in the process of its thermal decomposition were not larger than 30 K. At least 20 experiments have been carried out for each FCM.

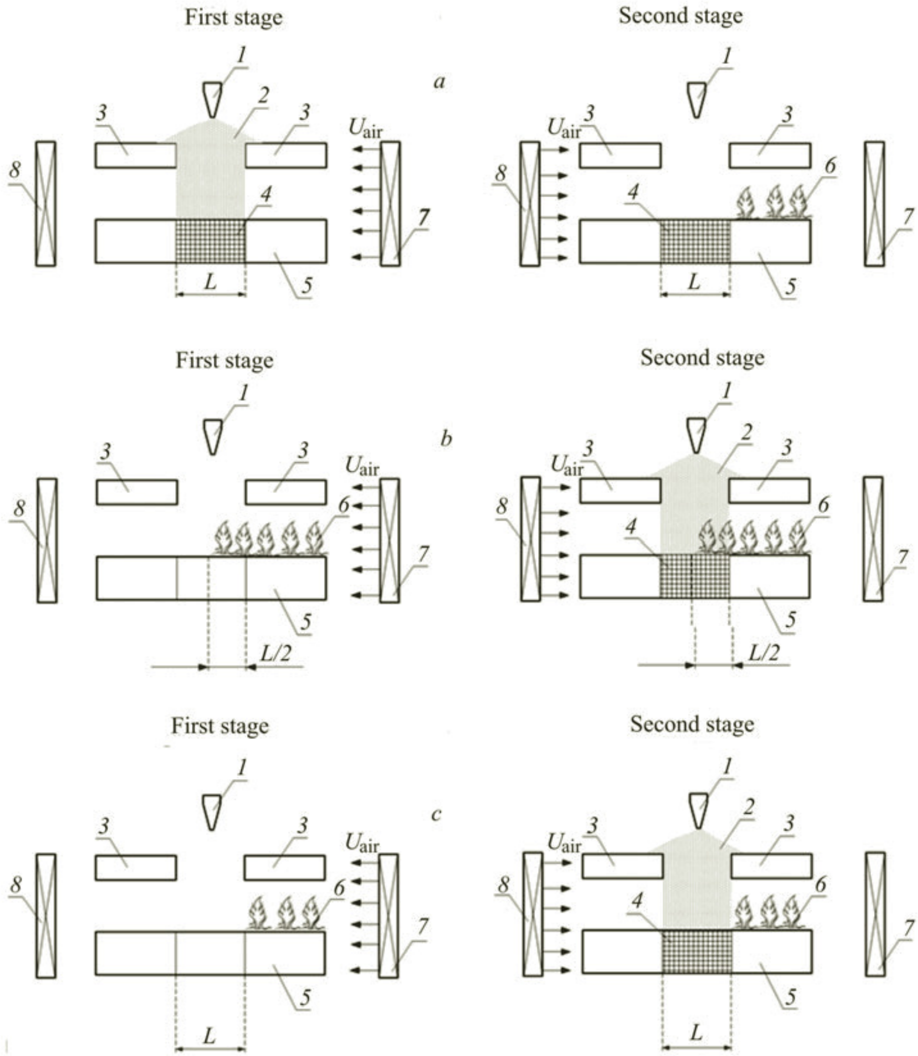

Fig. 2. Schemes of spraying of water upstream of the front of combustion of a FCM (a); over the combustion front (b), and upstream of the combustion front and over it (c): 1) sprayer; 2) water aerosol; 3) vessels for water; 4) liquid aerosol; 5) pan with a FCM; 6) flame; 7, 8) air blowers.

Results and Discussion. Figure 3 shows dependences of the times of termination of the flame combustion and thermal decomposition of a FCM, obtained in the cases where a water droplet flow was supplied to the FCM by the above-described three schemes. The experiments were conducted under conditions where air began to move towards the combustion front at the instant this front reached the edge of a water screen. In the case where a FCM was humidified in advance (the first scheme), the following effects were observed. After the FCM was ignited, an air flow pressed the flame to the FCM surface, with the result that the products of combustion of the FCM were intensively blown into its nonreacting zone, and the velocity of movement of the combustion front increased. Once the combustion front reached the FCM region humidified in advance with water, a countercurrent air flow was formed. This flow turned the flame about and, in so doing, prevented the development of the thermal-decomposition reaction in the FCM and the drying of its components found in the region of action of the liquid aerosol. In the cases where water was sprayed over a FCM by the second and third schemes, the movement of the combustion front was retarded not only by its turn in the opposite direction but also by the water droplets carried by the air flow. The flame combustion of the FCM was terminated practically at once because water was supplied to the FCM region having a maximum temperature.

It was established in preliminary experiments that the minimum necessary width of a water droplet flow should be 50 mm. We also determined the minimum water-spraying time necessary and sufficient for the suppression of the flame

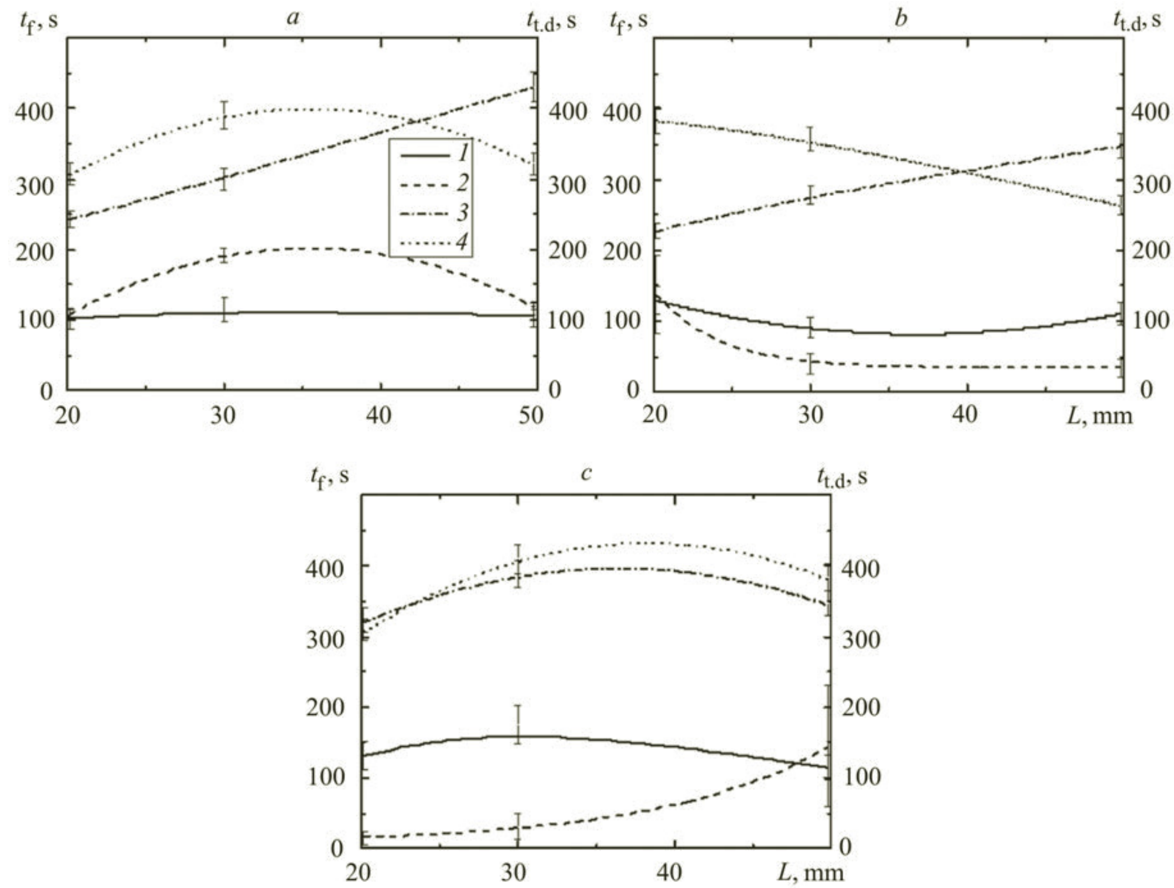

Fig. 3. Dependences of the times of termination of the flame combustion (1, 2) and thermal decomposition (3, 4) of a FCM mixture on the width of a water droplet flow acted upon by a favoring air flow (1, 3) and an adverse air flow (2, 4) with a velocity $U_{air} \approx 1.3$ m/s for the first (a), second (b), and third (c) schemes of water spraying.

combustion and thermal decomposition of a FCM. Experiments were conducted with the use of water-droplet flows of width 50 mm and smaller widths, and water was sprayed over FCM samples by the three schemes during minimum times determined for a water droplet flow with $L \approx 50$ mm.

Figure 4 presents dependences of the times of termination of the flame combustion and thermal decomposition of a FCM mixture and birch leaves on the transverse size of the water-droplet flow acting on them. It was established that a decrease in the width of a water-droplet flow does not lead to a decrease in the time of suppression of the flame combustion of a FCM (the deviations comprised ~3–12%). However, the time of termination of the thermal decomposition of a FCM decreased markedly in this case, and this decrease comprised 42% for the FCM mixture and 45% for the birch leaves. The effects observed are explained by the fact that a decrease in the transverse size of the aerosol flow acting on a FCM makes it possible to increase the specific density of the water supplied to the FCM to a maximum and, accordingly, to decrease the time of drying of the material subjected to the action of the liquid aerosol to a minimum. Figure 5 shows typical videograms of the process of suppression of the combustion of birch leaves by the first scheme of water spraying with a water droplet flow of width 30 mm.

The minimum times of water spraying and the corresponding widths of the water droplet screens necessary for the suppression of the flame combustion and thermal decomposition of the forest combustible materials being investigated are presented in Table 1. Analysis of these data allows the conclusion that, in the case of spraying of water over a FCM by the first scheme, the FCM is humidified across the whole of its thickness (the humidification thickness h_h was determined from the thermocouple measurements). It has been established that the use of the second and third schemes of water spraying makes it possible to completely suppress the combustion of a FCM. The results of our investigations show that, in the process

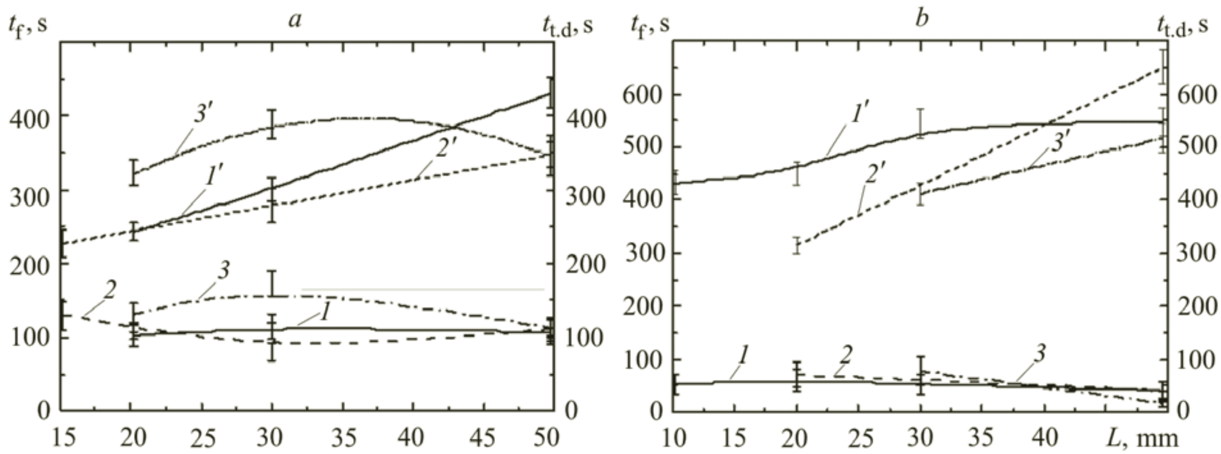

Fig. 4. Dependences of the times of suppression of the flame combustion (1–3) and thermal decomposition (1′–3′) of a FCM by the first (1, 1′), second (2, 2′), and third (3, 3′) schemes on the thickness of the water screen under the conditions of a favoring air flow with a velocity $U_{air} \approx 1.3$ m/s: a) FCM mixture; b) birch leaves.

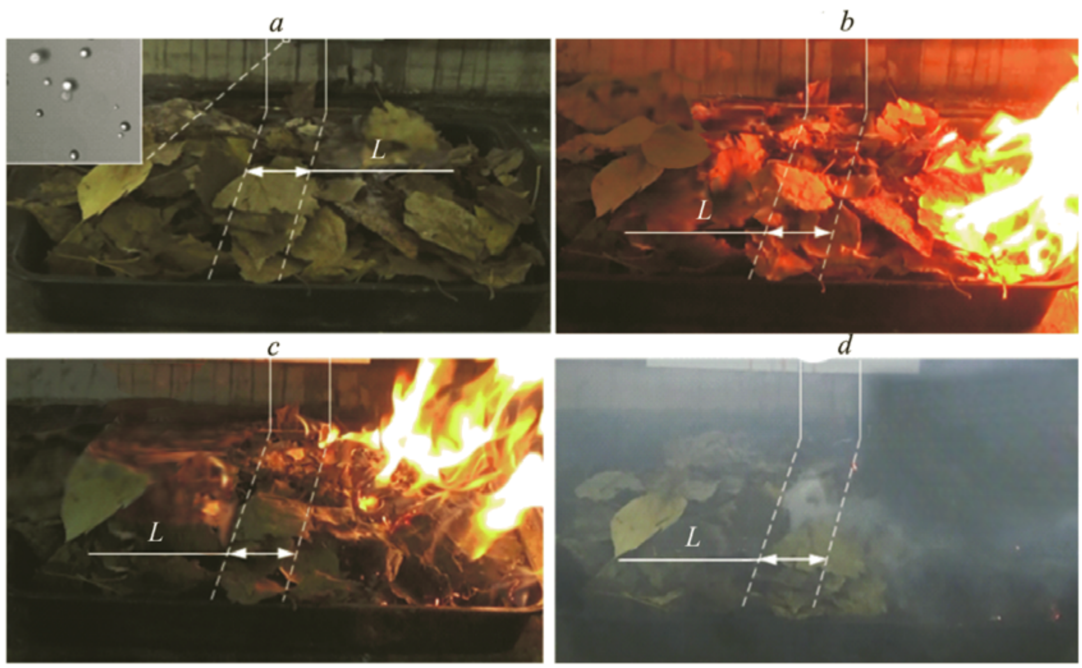

Fig. 5. Videograms of the suppression of the combustion of birch leaves by the first scheme at L = 30 mm: a) t = 0; b) t = 13 s (intensification of combustion of the FCM); c) t = 31 s (a flame reached the edge of a water droplet flow); d) $t = t_f$ = 61 s (localization of the flame combustion of the FCM).

of pyrolysis of leaves and a FCM mixture, the surface layer of a FCM burns out, which is favorable for the penetration of water deep into the material. However, the water supplied to a FCM is insufficient to humidify it in its width because a part of the liquid spent for the fire extinguishing evaporates in the combustion zone. In the experiments with birch leaves, the fire propagated in the upper layer of their samples, which is explained by the fact that these leaves represent an almost monolithic material. Because of this, in the cases where water was sprayed by the first and second schemes and a water droplet flow of width as small as 10 mm was used, the combustion front failed to penetrate through the water screen. Water droplets accumulated on the surface of the FCM and, in so doing, prevented the propagation of the flame. The maximum width of a

TABLE 1. Conditions Necessary for the Suppression of the Flame Combustion and Thermal Decomposition of a FCM by the Three Water-Spraying Schemes

Fire extinguishing parameters	First scheme		Second scheme		Third scheme	
	Leaves	FCM mixture	Leaves	FCM mixture	Leaves	FCM mixture
t_{min}, s	25	15	10	10	10	10
L, mm	10	20	20	15	30	20
h_h, mm	40	40	22	22	26	22

water droplet flow in these experiments was 30 mm. Our investigations of the suppression of the flame combustion and thermal decomposition of a mixture of leaves, needles, and twigs allowed us to determine the minimum width of a water droplet flow necessary for each of the three schemes of water spraying (Table 1). In the case where a water droplet flow of minimum width was used, the front of combustion of a FCM overcame a water screen of smaller width, and the FCM burnt down incompletely. In the majority of experiments, the combustion front did not reach the screen edge. The remaining mass of the FCM comprised 50% of its initial mass, and not the whole water sprayed evaporated in the process of suppression of the fire (in the case of fire extinguishing by the first scheme, water remained in the pan after the thermal decomposition of the FCM was suppressed). It should be noted that the structure of a FCM influences the characteristics of its thermal decomposition and the physicochemical processes proceeding in it under the conditions of interaction of the FCM with the water supplied to it [21–24]. For example, leaves prevent the movement of water droplets deep into their layer, with the result that water droplets accumulate on the surface of the material and form a film on it [21]. Undoubtedly, the spraying of water upstream of the front of combustion of a FCM or by the combined scheme makes it possible to intensify the heat transfer from the combustion zone due to the accumulation of heat in the layer of water in the process of its heating and intensive evaporation [22]. In the case where water interacts with an FCM mixture consisting mainly of needles and twigs, another effect is observed: water droplets rapidly penetrate through the highly porous structure of this FCM and reach its low-temperature layers [23, 24]. In this case, water covers only individual needles and twigs and practically does not stay in a FCM layer. To decrease the time of suppression of the flame combustion and thermal decomposition of such a material to a minimum, it is advantageous to spray water by the combined scheme, i.e., upstream of its combustion front and over this front.

Conclusions. The results of our experimental investigations can be used as a database in the development of prognostic physical and mathematical models which would make it possible to determine effective conditions of suppression of the flame combustion and thermal decomposition of forest combustible materials. Most important of all that we determined is the influence of air flows (the wind load) on the conditions and characteristics of the interaction of a water aerosol with the combustion front of an FCM. With the use of the experimental data obtained, one can determine the conditions under which the wind load on the process of extinguishing a forest fire is minimum.

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NOTATION

h_h, thickness of are humidified FCM layer, mm; L, transverse size of a water droplet flow, mm; P, pressure in the vessel with water, atm; R_d, radius of a water droplet, mm; t_f and $t_{t.d}$, times of termination of the flame combustion and thermal decomposition of a FCM, s; t_{min}, minimum time of water spraying, s; T_{FCM}, temperature within a FCM layer, K; U_{air}, velocity of an air flow; ζ_{FCM}, specific density of the water supplied to a FCM, $L/(m^2 \cdot s)$. Subscripts: air, air; f, flame; h, humidification; min, minimum; t.d, thermal decomposition.

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