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HEAT AND MASS TRANSFER IN COMBUSTION PROCESSES

INFLUENCE OF THE DENSITY OF A FOREST COMBUSTIBLE MATERIAL ON THE SUPPRESSION OF ITS THERMAL DECOMPOSITION BY A LIQUID AEROSOL

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Experimental investigations on the characteristic time of suppression of the thermal decomposition of the soil cover of coniferous and foliage forests and on the volume of water required for this purpose have been performed. Experiments were conducted with samples of typical forest combustible materials (birch leaves and spruce needles) of different densities under conditions characteristic of a forest fire extinguished by a liquid aerosol with the use of modern fire-extinguishing means. It was established that it makes no sense to increase the volume of water used for suppression of the ignition of a forest combustible material whose density exceeds a definite limiting value.

Keywords: *forest combustible material, hotbed of fire, thermal decomposition, flame combustion, suppression of combustion, water, aerosol flow.*

Introduction. Forest fires are a source of global environmental, economic, and social problems for many countries in the world [1–3]. Russia has a world lead in the area of its boreal forests [4, 5]. In 2015, the territories of the Far Eastern, Siberian, and Urals federal districts passed by fire amounted to about 95% of the entire territory of Russia where forest fires of different categories (ground, crown, mixed) took place. It is known [6, 7] that the main part of a forest burns in the regime of ground fire and that the low ignition of a boreal zone most often causes a crown fire (fast or sustained) [5–7]. Liquidation of such natural calamities is complicated by the weather conditions and the daily cycle of a fire [8]. Since forest fires arise most often under the conditions of prolonged absence of atmospheric precipitation and high temperatures, unfavorable for the suppression of fire, effective fire-extinguishing technologies are required.

To stop pyrolysis and flame combustion of a forest litter, a local throw-down of an extinguishing liquid from an airplane or a helicopter to a combustion zone is used as a rule [9–11]. Investigations have shown that, in this case, the pyrolysis reaction in the layers of a boreal mass is not suppressed because the water thrown down to it is concentrated on a small area of its surface and penetrates into the ground, and only 5–7% of this water is expended in decreasing the temperature of the thermal decomposition of a forest combustible material (FCM) [12]. Estimation of the usable volume of a liquid thrown down from an aircraft to a fire is a pressing problem because of the high cost of aviation fire extinguishing.

The thickness of a forest litter, as a rule, does not exceed 20 cm [16–18]. In it, three horizons (upper, middle, and lower) are distinguished. The lower horizon of the litter is characterized by a high concentration of mineral substances. When the front of combustion moves over the tree waste of a boreal forest, the upper horizon of the forest litter, whose density depends substantially on the forest age, mainly burns out. The density of the litter of a young forest varies within a wide range. In a boreal big stand having a large growth time, the density of the vegetation cover is the highest since it includes tree branchlets that aid in the formation of a caked litter. It is known [16–18] that the upper layer of a spruce-needle waste has a density of 30–33 kg/m^3, and the density of a foliage-tree waste is 8–12 kg/m^3. In summer dry periods, a very dangerous fire situation can arise in a forest in the case where the front of a fire moves over the fresh tree waste forming the upper tier of the forest combustible materials [16–18]. In this connection, of interest is estimation of the conditions necessary for the termination of the pyrolysis of the FCMs in a boreal forest depending on the density of its cover forming over the period of several days to several years.

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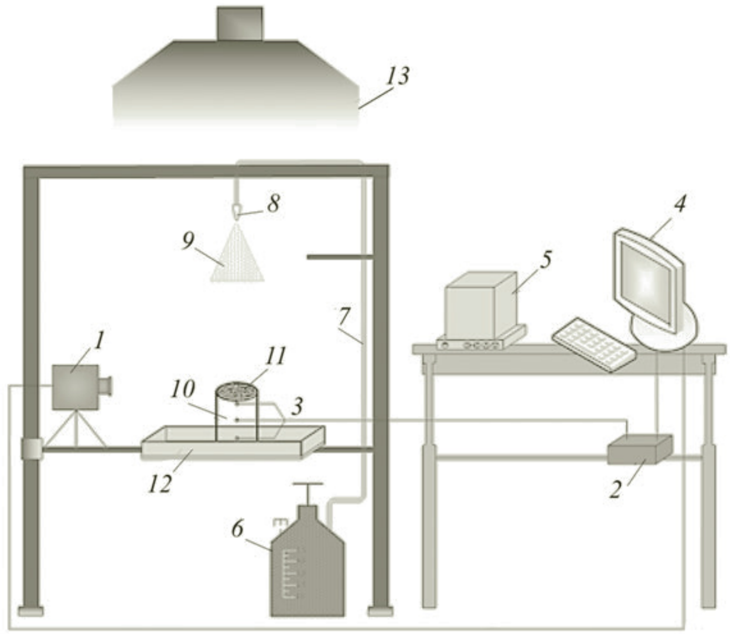

Fig. 1. Diagram of the experimental stand: 1) high-speed video camera; 2) analog input module; 3) thermocouples; 4) working station; 5) microbalance; 6) vessel with water; 7) channel for supply of water; 8) atomizing nozzle; 9) liquid aerosol; 10) cylinder with a FCM; 11) FCM; 12) metallic pan; 13) exhaust system.

The aim of the present work is to experimentally investigate the conditions of suppression of the reaction of thermal decomposition of a forest combustible material by a liquid aerosol (used as a rule in fire-extinguishing systems) depending on the density of the FCM.

Experimental Stand and Investigation Methods. The experiments were carried out with samples of birch leaves and spruce needles. A diagram of the experimental stand is shown in Fig. 1. The main meaningful parameters of the rapid thermal decomposition of a FCM and the heat and mass transfer in the process of its combustion were determined using quick-response thermocouples, high-speed video recording, and a hardware–software complex providing the realization of panoramic optical diagnostic methods.

Before an experiment, a FCM was subjected to special thermal drying, and its initial moisture content was determined. The relative moisture content of a FCM was calculated by the formula $\gamma_f = (m_{fm} - m_{f2})\cdot 100$. The moisture content of the birch leaves was 5–8%, and that of the spruce needles was 7–10%. A FCM sample was weighed on microbalance 5 and placed in the model hotbed of fire 9. The initial mass of a FCM was selected so that its density in each series of experiments performed under identical initial conditions changed within a small range corresponding to the experimental error. The density of a FCM was calculated by the formula $\rho_f = m_{f0}(h_f S_f)$, where $S_f = \pi(d_f/2)^2$. The range of change in the density of a FCM sample was selected so that the values of ρ_f correspond to the density of a forest litter burning in a ground fire. It is known [15] that a forest litter formed for years has a higher density compared to the density of a fresh tree waste. In the experiments, the density of a FCM placed in a model hotbed of fire was varied from 10.75 to 52.98 kg/m^3 for the birch leaves and from 27.26 to 52.78 kg/m^3 for the spruce needles. FCM samples were placed in hollow corrugated aluminum cylinders of height h_f = 0.04 m and diameter d_f = 0.06 m.

Experimental investigations were carried out in two stages. In the first stage, the time of burning of the FCMs was determined. A FCM sample was placed on a metallic pan 12. The temperature of the FCM was measured by the chromel-alumel needle thermocouples 3, positioned at three points along the height of cylinder 10, in the temperature range 223–1473 K with a systematic error of ±3 K and a time lag not larger than 0.1 s. The open surface of a model hotbed of fire was ignited with the use of three piezoelectric gas burners. Simultaneously with the initiation of combustion of a FCM sample, the time began to be read on an electronic stopwatch with a step of 0.01 s. The combustion of a FCM was considered as stable when the temperature in its layer T_{fi} was higher than 370 K. In the second stage, the time of suppression of the reaction of thermal

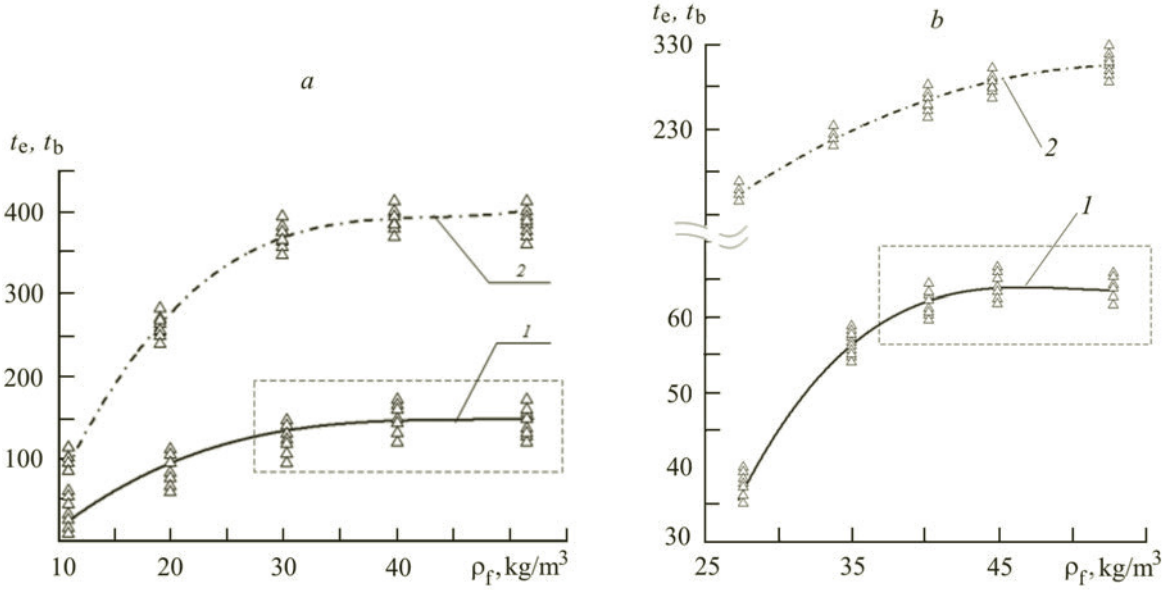

Fig. 2. Times of extinguishing t_e (1) and burning t_b (2) of birch leaves (a) and spruce needles (b) depending on their density at R_d = 0.01–0.12 mm, $h_f \approx 0.04$, and $d_f \approx 0.06$ m.

decomposition of a FCM t_e under the action of a liquid aerosol and the volume of water consumed V_e were determined. The pressure in the system of injection of water was $P = 1.3$ Atm. The atomizing nozzle 8 generated droplets of size R_d = 0.01–0.12 mm. The density of spraying of a hotbed was ξ_f = 0.014–0.016 L/(m^2·s) at a water flow rate μ_w = 0.00063 L/s. The volume of a distilled water (State Standard 6709-72) sufficient for the extinguishing of a model hotbed of fire was determined. To do this, we measured the time within which the pyrolysis of a FCM was terminated. The termination of the reaction of thermal decomposition of a FCM was determined by the temperatures at three points of its sample. The decrease in the temperature of a FCM layer to 370 K, determined by the indications of the three thermocouples, was considered as a condition for the suppression of the thermal decomposition of the FCM. The time of suppression of the thermal decomposition of a FCM t_e was compared with the time of its burn-out t_b determined earlier. It was thought that the suppression of the thermal decomposition of a FCM is performed effectively if the condition $t_e \ll t_b$ is fulfilled.

Simultaneously with the spraying of water over a model hotbed of fire, the results of an experiment were processed by the optical diagnostic PIV (particle image velocimetry) and SP (shadow photography) methods on computer 4 with the use of the special Actual Flow software. The velocity of a droplet flow was determined using the PIV method in much the same way as in [19]. The sizes of the droplets in a dispersed flow were calculated by the SP method [20]. After the completion of each second-series experiment, the excess water in the metallic pan 12 was collected in a measuring sleeve, and the volume of this water V_{exc} was determined. The volume of the water expended in the extinguishing of a model fire by a liquid aerosol was calculated by the formula $V_e = \mu_w t_e - V_{exc}$. For each FCM, 15–20 experiments have been performed under identical initial conditions. The systematic errors of the experiments were $7 \cdot 10^{-6}$ m for R_d, 0.5 s for t_e and t_b, and $5 \cdot 10^{-4}$ L for V_e. The maximum accidental errors in determining T_f in the process of destruction of the FCMs were not larger than 8 K.

Results and Discussion. Results of an experimental investigation of the suppression of the reaction of thermal decomposition of a FCM under the action of a liquid aerosol depending on the density of the FCM are presented in Figs. 2 and 3. The spraying density was determined by the values of V_e calculated for a unit area of a fire. It is seen from these figures that the time of suppression of the pyrolysis of a FCM and the volume of water required for this purpose substantially increase with increase in the density of the FCM from 10 to 30 kg/m^3. This result is especially characteristic of the experiments with birch leaves. To suppress the reaction of thermal decomposition of a fresh waste of birch leaves, whose density comprises 8–12 kg/m^3 as a rule [16–18], it is necessary to continuously spray a liquid aerosol over a hotbed of fire for a time as long as 60 s. In this case, the required volume of water V_e is not larger than 0.006 L. It is known that a forest litter formed for years has a higher density [15, 18]. The times of suppression of the thermal decomposition of FCM samples with a density $\rho_f \approx$ 15–52 kg/m^3 varied from

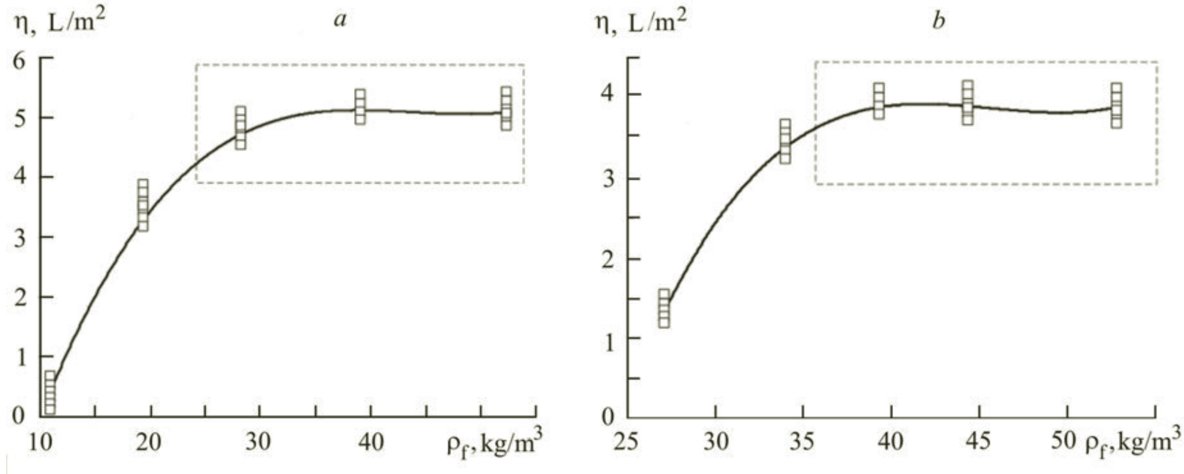

Fig. 3. Density of spraying of birch leaves (a) and spruce needles (b) depending on their density at $h_f \approx 0.04$ and $d_f \approx 0.06$ m.

60 to 15 s, and the volume of the water consumed was equal to $V_e = 0.006–0.015$ L. In the measurement system adopted by rescue services, this volume corresponds to the characteristic specific density of spraying of water over a unit area of a fire $\eta = 0.4–5$ L/m^2. The specific flow rate of water per unit area of a fire or the density of its spraying $\eta = V_e/S_f$, recommended by fire departments all over the world, falls within the range 3–5 L/m^2 [10–12]. The data presented in Fig. 3 allow the conclusion that the existing technologies of aviation extinguishing of forest fires have a great potential for development in the direction of rational use of water for suppression of a fire and, consequently, decreasing the density of its spraying to 3 L/m^2 and smaller values.

It was established that the time of suppression of the pyrolysis of spruce needles (Fig. 2b) and the volume of water required for this purpose (Fig. 3b) increase somewhat with increase in their density. In our experiments, the time of suppression of the pyrolysis of the spruce needles increased by 20–25 s with increase in their density from 27 to 35 kg/m^3 (the density of the upper vegetation cover of a coniferous forest comprises, as a rule, 30–33 kg/m^3 in the case of ground fire in it [16–18]). For the samples of spruce needles with densities of 35–52 kg/m^3, the values of t_e and V_e differed by no more than 14% and 18%, respectively. The result obtained is explained first of all by the structural features of the FCMs being investigated. Our investigations have shown that, as the density of birch leaves increases, they form a practically monolithic near-surface layer. Within 10–15 s after the beginning of the spraying of water over the birch leaves, water droplets formed a thin liquid film on their surface, and a fairly limited mass of water penetrated into the deep layers of the leaves because of their complex multitier structure. In this case, one of the most common extinguishing mechanisms is realized: the thermal-decomposition reaction proceeds along the whole height of a sample, and, to decrease the temperature in it, it is necessary to provide continuous spraying of water within a definite time, which leads to an increase in the volume of water required for the extinguishing of a fire. In the experiments with birch leaves, the thermal decomposition of their samples was suppressed only under conditions where water penetrated into the deep layers of a sample, which was attained in the case where an increase in the thickness of the film on the surface of these leaves led to an increase in the forces exerting pressure on their layers and caused the transfer of moisture through the elements of the porous structure of this material. The density of the surface cover in foliage forests, as a rule, does not exceed 8–12 kg/m^3. Therefore, the dense layers of the waste are in its middle tier, whose thermokinetic and thermophysical parameters differ from those of the upper horizon [16–18]. Because of this, the times of suppression of the pyrolysis of birch leaves, obtained in our experiments, can be taken as the maximum times of suppression of the thermal decomposition reaction in the layers of the surface cover of leaves. In the experiments with spruce needles, the time of suppression of their pyrolysis and the volume of water required for this purpose changed moderately, as compared to the birch leaves, with increase in the density of the FCM, which is most probably due to the features of its structure. Water droplets penetrate deeper into a thermally decomposing layer of spruce needles, as compared to the birch leaves, and, in so doing, decrease the temperature of its layers. This effect is also responsible for the difference between the values of t_e for birch leaves and spruce needles.

The results obtained allow the conclusion that the parameters of suppression of the pyrolysis of a forest three waste are determined by its density. In particular, the increase in the density of a layer of birch leaves to 35 kg/m^3 leads to a large increase in the time of suppression of their thermal decomposition and in the volume of water required for this purpose. This effect for spruce needles is much weaker. The laws revealed in our experiments can be used for the development of models of heat transfer in closed systems with intensive heat release [21–23]. In Figs 2 and 3, the dashed lines define the limits within which t_e and V_e change insignificantly with increase in the density of a FCM. The above-described mechanism of influence of the density of a FCM layer on the conditions of suppression of its thermal decomposition allows us to formulate the following hypotheses. As the density of a FCM increases and, accordingly, its layered porous structure changes, the resistance to the water flow through the FCM increases and the penetration of water droplets into its deep layers slows down under the conditions of heating of the FCM to the temperature higher than the temperature of its thermal decomposition. In this case, the main endothermic phase transformations proceed not everywhere through the width of the FCM but only in its upper part. However, as the results of our experiments show, the intensive evaporation of water in this region is sufficient for substantial decreasing the temperature throughout the thickness of the FCM, i.e., for the litter of each FCM there is a threshold density beyond which it is meaningless to increase the volume of the spraying water. The formation of a surface cover of spruce needles for several years does not lead to a substantial increase in t_e and V_e. The necessary and sufficient condition for the suppression of the pyrolysis of the surface cover in a coniferous forest is the supply of a liquid aerosol to it within 70 s. Such a small-duration process of spraying of water over a forest fire can be provided with the use of a fairly small group of aircrafts (3 to 5). However, this process can be effective only in the case where water is sprayed over the entire surface of a thermally decomposing FCM.

Conclusions. Our experimental investigations allowed us to determine the characteristic time of suppression of the thermal decomposition of a FCM and the volume of water required for this purpose depending on the density of the FCM. It was established experimentally for the first time that the density of a FCM only at its definite value substantially influences the process of thermal decomposition of the FCM. For example, the volume of water required for the suppression of pyrolysis of a waste of spruce needles formed for years practically does not change with change in the density of this waste. The data obtained allow one to determine the conditions of termination of the reaction of thermal decomposition of the FCMs in forests with different seasons of fall of leaves and twigs. It is important to take into account the effects revealed in determining the rational time of spraying of water over a forest tract and the corresponding volume of water.

NOTATION

d_f and h_f, diameter and height of a model hotbed of fire, m; m_{f0}, initial mass of a FCM sample, g; m_{fm} and m_{fdr}, masses of a FCM sample before and after the thermal drying, g; P, pressure in the vessel with water, atm; R_d, radius of a water droplet, mm; S_f, surface area of a FCM, mm^2; t_b, time of burning of a FCM without action of water on it, s; t_e, time of extinguishing of a hotbed of fire, s; T_{fi}, temperature of the ith layer of a FCM, K; V_e, volume of water expended in the extinguishing of a hotbed of fire, liter; V_{exc}, volume of the excess water in the pan, liter; γ_f, relative moisture content of a FCM, %; η, density of spraying, liter/m^3; μ_w, specific flow rate of the water sprayed by an atomizing nozzle, liter/s; ρ_f, density of a FCM, kg/m^3; ξ, specific density of spraying, liter/(m^2·s). Subscripts: b, burning; dr, dry; e, extinguishing; exc, excess; f, forest; m, moist; w, water.

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