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HEAT AND MASS TRANSFER IN COMBUSTION PROCESSES

SUPPRESSION OF THE THERMAL DECOMPOSITION REACTION OF FOREST COMBUSTIBLE MATERIALS IN LARGE-AREA FIRES

R. S. Volkov, A. O. Zhdanova, G. V. Kuznetsov, and P. A. Strizhak

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Experimental investigations on the characteristic time of suppression of the thermal decomposition reaction of typical forest combustible materials (aspen twigs, birch leaves, spruce needles, pine chips, and a mixture of these materials) and the volume of water required for this purpose have been performed for model fire hotbeds of different areas: S_{FCM} *= 0.0003–0.007* m^2 *and* S_{FCM} *= 0.045–0.245* m^2*. In the experiments, aerosol water flows with droplets of size 0.01–0.25 mm were used for the spraying of model fire hotbeds, and the density of spraying was 0.02 L/(*m^2*·s). It was established that the characteristics of suppression of a fire by an aerosol water flow are mainly determined by the sizes of the droplets in this flow. Prognostic estimates of changes in the dispersivity of a droplet cloud, formed from large (as large as 0.5 L) "drops" (water agglomerates) thrown down from a height, have been made. It is shown that these changes can influence the conditions and characteristics of suppression of a forest fire. Dependences, allowing one to forecast the characteristics of suppression of the thermal decomposition of forest combustible materials with the use of large water agglomerates thrown down from an aircraft and aerosol clouds formed from these agglomerates in the process of their movement to the earth, are presented.*

Keywords: *forest combustible materials, thermal decomposition, hotbed of fire, aerosol flow, water mass.*

Introduction. Forest fires represent a global problem for the world community. The consequences of the ignition of boreal zones enormously damage the environment and the economics of states [1–3]. For example, statistical data on the large forest fires (of area larger than 1000 ha) in Greece [1] show that the ignition even of a very small region of a boreal zone under certain conditions, determined by the temperature and relative humidity of the air and the velocity of the wind, can turn to the stage of fire over an immense area. On the basis of system analysis of the information on fires in the territory of Portugal, whose number for the last five years adds up to 127, 490 [2], specialists have inferred that large fires arise most often on areas covered with bushes. These findings point to the complex interconnection between the creeping and crown forest fires, which should be taken into account in deciding on the technology of suppression of forest fires.

Creeping and crown fires on large areas are suppressed as a rule with the use of aircrafts [3]. In the United States, large flying tankers are actively used for the suppression of forest fires arising in the course of a long-continued drought [3]. Spanish specialists have experience [4] of using unmanned aircrafts for the efficient suppression of forest fires in large areas. The Ministry of Emergency Situations of Russia has about 50 aircrafts of the Il-76, Be-200, Mi-8, Mi-26T, and other marks in its disposal, and it is one of the most expeditious formations in the world. Russia has repeatedly provided help in the suppression of forest fires in the territories of Portugal, Bulgaria, Montenegro, Serbia, and Greece. However, as objective data show [3–8], any state is always short in aircraft in the suppression of large fires in its territory.

As a rule, a liquid is thrown down from an aircraft to a fire zone in the form of agglomerates having a mass from 1–3 t to 40 t [5–8]. For example, a Be-200 amphibian can transport as large as 12 t of a fire-extinguishing substance, and an Il-76 airplane can deliver 40 t of such a substance to a fire zone [6]. Unfortunately, the many years′ experience on the use of aircrafts for the liquidation of ignition of a forest zone gives no way of formulating recommendations that would make it possible to substantially increase the efficiency of suppression of a forest fire. It was shown in [9–11] that, in the case of

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National Research Tomsk Polytechnical University, 30 Lenin Ave., Tomsk, 634050, Russia; email: zhdanovaao@tpu.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 91, No. 2, pp. 434–442, March–April, 2018. Original article submitted August 16, 2016.

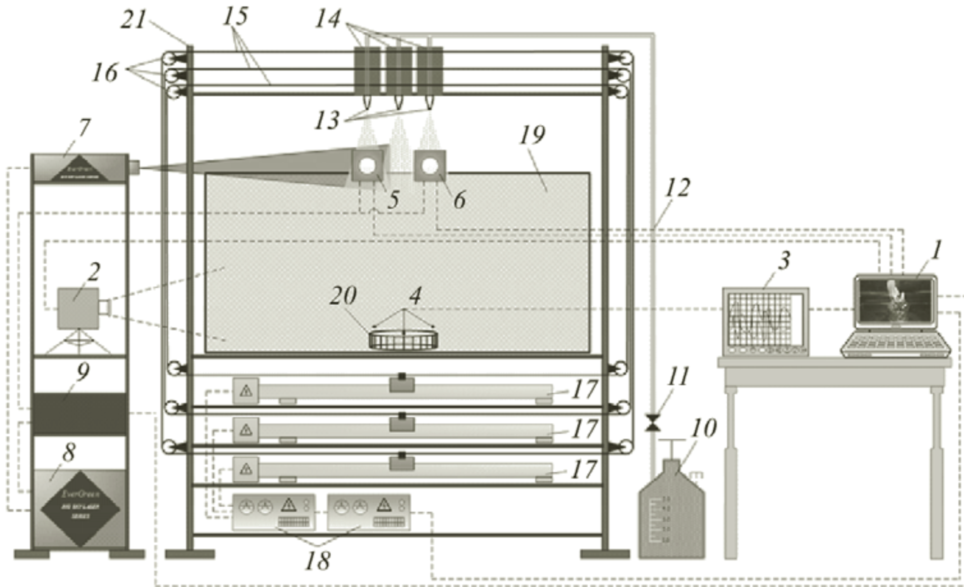


Fig. 1. Fig. 1. Diagram of the experimental stand: 1) personal computer; 2) high-speed video camera; 3) technological multichannel recorder; 4) thermocouples of type K; 5, 6) cross-correlated video cameras; 7) double pulsed Nd:YAG laser; 8) generator of laser radiation; 9) synchronizer of the personal computer, the cross-correlated video camera, and the Nd:YAG laser; 10) vessel with a liquid; 11) locking gate; 12) channel for supply of the liquid; 13) atomizers; 14) carriages for attachment of the atomizers; 15) ropes; 16) roller mounts; 17) motorized coordinate mechanisms; 19) reservoir; 20) pan with a FCM; 21) metallic case.

suppression of a forest fire with the use of an aircraft, of crucial importance are the evaporation characteristics of large masses of water and water droplets moving through a high-temperature gas medium. Therefore, to improve a technology of aviation suppression of a forest fire, it is necessary to have reliable experimental data on the movement of the water masses thrown down from an aircraft and on the area covered by them, which could be used for the prediction of the conditions of a large forest fire and for deciding on the methods of its suppression.

The aim of the present work is to determine the characteristic time of suppression of the thermal decomposition of forest combustible materials (FCM) on large areas, the volume of water required for this purpose, and the optimum method for supply of water to a combustion zone.

Experimental Stand and Investigation Methods. The investigations were performed on an experimental stand, representing a system for suppression of a model hotbed of fire (Fig. 1). Model fire hotbeds were inserted into reservoir 19 placed in the metallic case 21. The reservoir is shaped like a parallelepiped and has walls of acrylic resin of thickness 5 mm. For the prevention of the melting of the bottom and walls of the reservoir in the process of burning of a model fire hotbed in it, they are additionally covered with asbestos sheets of thickness 10 mm. A liquid flow for spraying of a fire hotbed is formed by atomizers 13 producing a polydisperse flow of droplets of radius R_d = 0.01–0.25 mm. The supply of water to the atomizers is provided by a system comprising vessel 10 filled with a water under a pressure of 50–300 kPa, a locking gate 11, and a heat-resistant channel 12. The characteristics of a droplet flow (the sizes and volume concentration of droplets and the initial velocity of their movement) were estimated with the use of the widely accepted panoramic optical PIV [12] and SP [13] methods for diagnostics of multiphase media.

Model fire hotbeds of class A (in accordance with the law of the Russian Federation No. 123-F3 "Technical Regulations of Fire Safety Requirements" dated July 22, 2008) of area S_{FCM} = 0.045–0.245 m^2 and small model fire hotbeds of area S_{FCM} = 0.0003–0.007 m^2 assembled of a hollow cylinder of height $h_{FCM} \approx$ 0.04 m made of a corrugated aluminum were investigated. The model fire hotbeds of class A were formed with the use of metallic pans filled with a FCM. Since, in the case of creeping fire in a forest, forest zones with coniferous and deciduous plantations burn out predominantly [14–18], as FCMs, we used birch leaves, spruce needles, aspen twigs, pine chips, and mixtures of these materials. The moisture content of the FCMs used in the experiments was 10–14% for the aspen twigs, 12–15% for the pine chips, 5–8% for the birch leaves, 7–10% for the spruce needles, and 8–12% for the FCM mixtures. To control the temperature of the thermal decomposition of a FCM, we equipped the model hotbeds of fire with three chromel-alumel thermocouples measuring temperature in the range 223–1473 K with a systematic error of ±3 K and an inertia not larger than 0.1 s.

All the experiments were carried out in two stages, at which the time of burn-out of a FCM t_b without injection of water into it (first stage) and the time of suppression of a model fire hotbed under the action of a droplet flow (second stage) were determined. For the suppression of the thermal decomposition of a FCM, a distilled water (State Standard 6709-72) was used.

The following procedures were performed.

1) A model hotbed of fire was formed, for which purpose pan 20 was filled with a FCM and was placed in reservoir 19.

2) The model hotbed of fire was ignited with the use of two piezoelectric elements to provide a uniform heating of the FCM.

3) Video recording of the suppression of the thermal decomposition of the FCM was started with the use of a high-speed (as high a 100,000 frame/s) camera 2.

4) The locking gate 11 in conduit 12 was opened, an atomizer began to move, and the extinguishing liquid was sprayed over the perimeter of the combustion region.

5) The liquid was sprayed until the model fire was completely suppressed, which was determined by the indications of thermocouples 4 and visually, and thereafter the video recording was terminated.

6) A video record was processed on a personal computer (PC) 1, and the time of suppression of the fire t_s was calculated.

7) The time of suppression of the thermal decomposition of the FCM t_s was compared with the time of its complete burn out t_b determined in advance. In the case where we obtained $t_s << t_b$, the parameters of injection of water into the hotbed of fire were considered as favorable for effective suppression of the fire.

8) After the completion of each experiment, the excess water in the metallic pan, in which a FCM sample burned, was collected in a measuring sleeve, and the volume of this water V_e was determined. In the experiments, the tendency for increasing V_e with increase in the dispersivity of a droplet flow was observed.

At least 10 experiments have been conducted for each model hotbed of fire. The time for which the indications of all the three thermocouples were smaller than the temperature of the onset of thermal decomposition of a FCM sample (370 K) was taken as the instant of dying of its combustion or burn-out of the FCM. After the completion of each experiment, the videograms of suppression of a fire were analyzed. The experiments in which the burning of a FCM sample over its cross section was inhomogeneous were not analyzed. The systematic errors in determining the parameters of the suppression of a fire were $7 \cdot 10^{-6}$ m for R_d, 2% for U_d, 0.5 s for t_s and t_b, and $5 \cdot 10^{-4}$ L for V_e. The maximum accidental errors in determining the temperature of the thermal decomposition of the FCM samples T_{FCM} were not larger than 15 K.

Results and Discussion. Analysis of the data presented in Fig. 2 shows that the area of a fire hotbed of class A moderately influences the time of suppression of the thermal decomposition reaction of the FCM in it t_s. This can be explained by the fact that, in the experiments, the specific density of spraying of model fire hotbeds by the droplet flows, provided by the atomizers, was constant and these flows covered the whole surface of the hotbeds uniformly. As a consequence, the times of suppression of the decomposition reaction of the FCMs in the hotbeds of fire having different areas differed by no more than 30–40 s. The small increase in the time t_s with increase in the area of a FCM can be explained by the fact that, in the majority of experiments, a layer of FCM remained in the central region of a model fire hotbed after the suppression process was terminated. The smoldering of this layer was observed during 15–40 s after the suppression of the thermal decomposition of the main mass of a FCM forming a model fire hotbed. With increase in the area of a model fire hotbed, the time of its smoldering and, consequently, the time required for the suppression of the fire increased. Measurements of the temperature of FCMs have shown that this peculiarity is due to the significant heat release at the center of a fire hotbed. The larger a hotbed, the larger the energy accumulated by it and the larger the temperature at its center.

The results of experiments with model fire hotbeds of class A (S_{FCM} = 0.045–0.245 m^2) and small model fire hotbeds (S_{FCM} = 0.0003–0.007 m^2) were compared and analyzed for all the FCMs being investigated. It was established that the times of suppression of the thermal decomposition reaction of a FCM in the model fire hotbeds of small and large area differ by 10–110 s. The mechanisms of suppression of the thermal decomposition of different FCMs were determined depending on their kinetic and thermophysical parameters. It was established that the determining characteristic of the suppression of the thermal decomposition reaction of a FCM is the initial temperature of this reaction that ranges from 350 to 500 K [14–20]

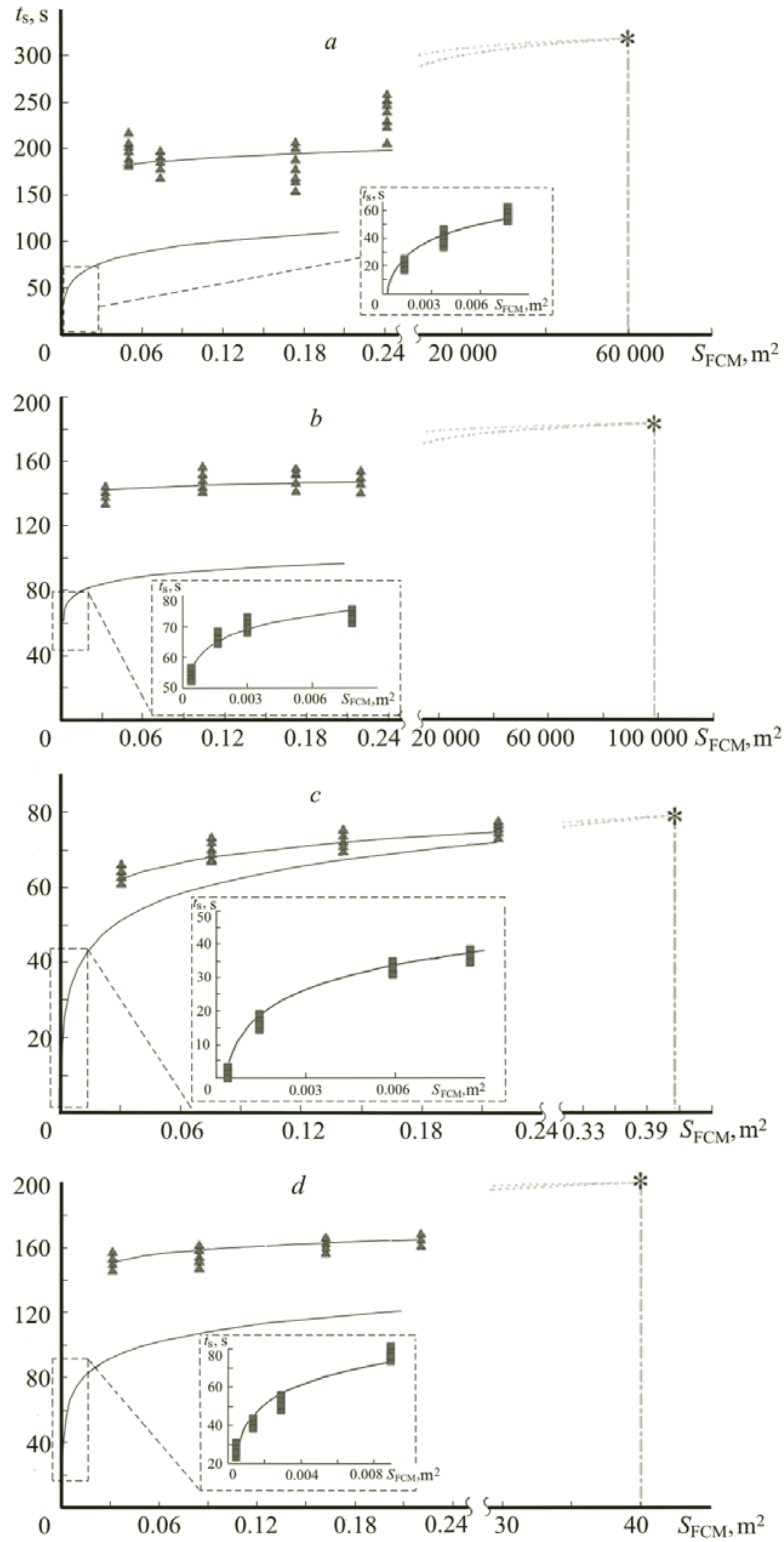


Fig. 2. Dependence of the time of suppression of a model fire hotbed on its area: a) mixture of fine chips (50%) and aspen twigs (50%); b) birch leaves; c) spruce needles; d) mixture of birch leaves (25%), spruce needles (15%), and aspen twigs (60%).

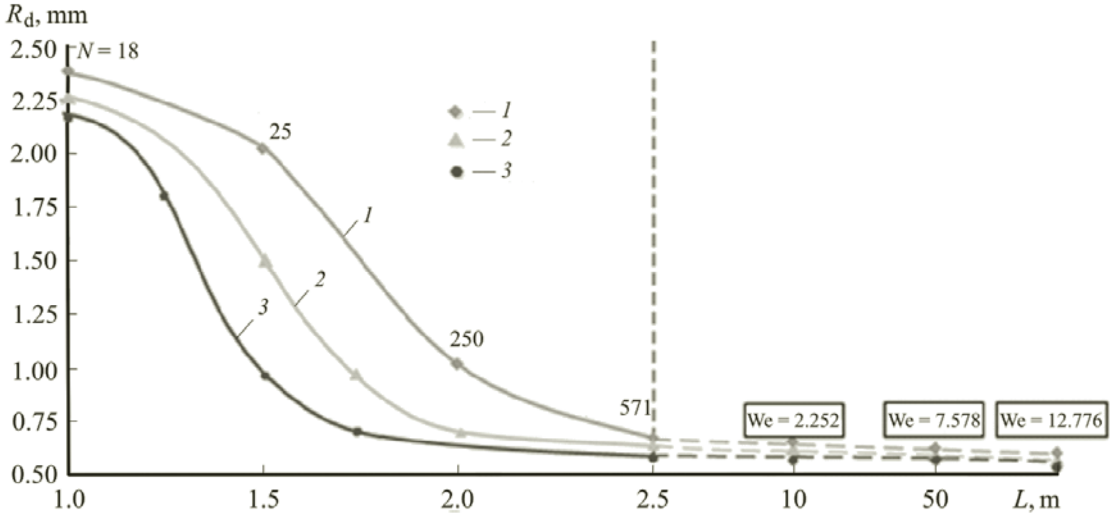


Fig. 3. Dependences of the sizes of the water droplets R_d in the water masses of volume V = 100 (1), 300 (2), and 500 mL (3) on the distance traveled by them L: full lines) calculation; points) experiment.

for the coniferous and deciduous species. The rates of thermal decomposition of FCMs change exponentially depending on their temperature. Because of this, a decrease in the temperature of the reacting layer of FCMs of one type even by 60–100 K can cause the suppression of the pyrolysis reaction in them, while, in FCMs of other types, the decomposition reaction can continue to proceed with a large rate under these conditions. Therefore, it is significant to determine the conditions of injection of water into a FCM under which the area of a fire hotbed will be covered uniformly and the temperature in the near-surface layer of the FCM will be substantially decreased. To solve this problem, it is necessary to determine the sizes of the droplets into which an almost monolithic large water mass can be divided in the process of its free fall from a height.

The experimental investigations on the sizes of the droplets into which a water mass is divided under the indicated conditions were performed in accordance with the methodology described in [21]. In the experiments, water agglomerates of volumes 100, 300, and 500 mL were thrown down from different heights falling within the range 0.5–2.5 m. The sizes of the droplets formed as a result of the breakage of these water masses in the process of their free fall in air are presented in Fig. 3. Analysis of these data shows that a water mass of volume 500 mL breaks down into droplets of smaller sizes compared to the sizes of the droplets into which the water masses of volumes 100 mL and 300 mL are broken down. Thus, the larger the water mass thrown down from a height, the smaller the droplets formed as a result of its breakage. This is explained first of all by the fact that large water masses have larger Weber numbers compared to those of small water masses. Consequently, the destruction and the subsequent disintegration of a large water mass begins earlier and proceeds more rapidly compared to those of a small water mass [21]. Results of the known experimental and theoretical works [9–11] allow the conclusion that the conditions of effective suppression of the thermal decomposition of a FCM are realized in the case where an extinguishing liquid is sprayed uniformly over the whole area of a fire. In the case where a hotbed of fire is subjected to the action of an aerosol (a cloud of small droplets), its temperature decreases due to the intensive evaporation of small droplets with formation of a water-vapor cloud and the removal of the combustion products from the hotbed. To provide effective evaporation of droplets in a flame and at the surface of a thermally decomposing FCM, it is necessary to control the sizes of water droplets. The data presented in Fig. 3 allow one to determine an optimum height from which a monolithic water mass should be thrown down in order to be divided into droplets of sizes required (appropriate) for the effective termination of the thermal reaction in the region of a forest fire.

Figure 4 shows the dynamics of change in the Weber number of water masses of different initial sizes depending on the change in their volume determined by the distance traveled by them in the process of their free fall in air under the conditions corresponding to the conditions of typical fall of a water mass thrown down from an aircraft. The data presented in Figs. 3 and 4 allow one to estimate the maximum sizes of the droplets into which a water mass thrown down from a height can be divided. It is seen that a water mass that has traveled a distance of 15–17 m in air is broken down into droplets of size 5 m, and, after it has traveled a distance larger than 100 m from the point of throw-down of this water mass, the maximum

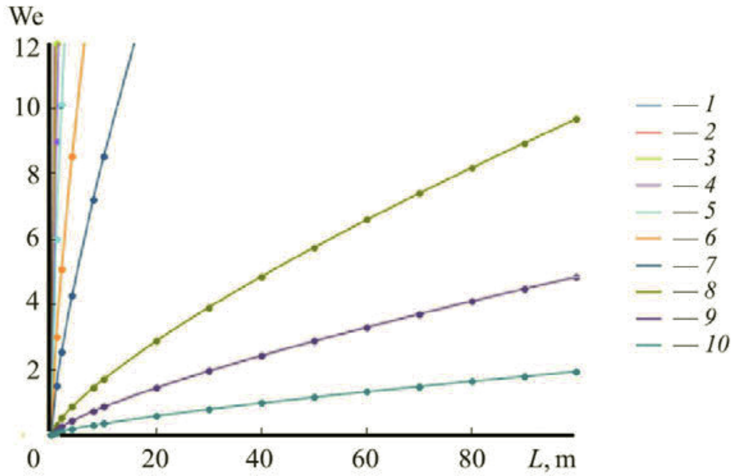
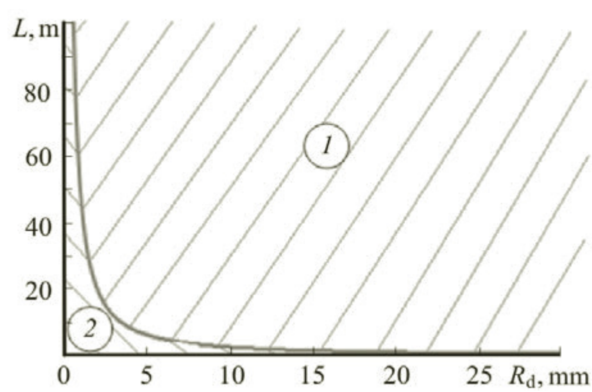


Fig. 4. Dynamics of change in the Weber number of water masses depending on the distance traveled by them in the process of free fall from a height: 1) R_d = 30 mm, V_d = 0.11 L; 2) 25, 0.06; 3) 20. 0.03; 4) 15, 0.01; 5) 10, $4.18 \cdot 10^{-3}$; 6) 5, $5.23 \cdot 10^{-4}$; 7) 2.5, $6.54 \cdot 10^{-5}$; 8) 0.5, $5.23 \cdot 10^{-7}$; 9) 0.25, $6.54 \cdot 10^{-8}$; 10) 0.1, $4.19 \cdot 10^{-9}$.



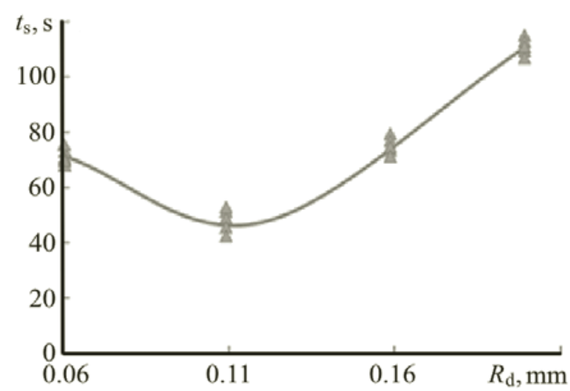


Fig. 5. Dependence of the sizes of the droplets in a water mass of volume $V \approx 500$ mliter on the distance traveled by it at We = 10: 1) region where the water mass is monolithic; 2) region of breakage of the water mass.

Fig. 6. Time of termination of the thermal decomposition reaction t_s of birch leaves in a fire hotbed of areas $S_{FCM} \approx 0.002$ m^2 depending on the sizes of water droplets R_d at $\xi = 0.02$ L/(m^2·s): full line) calculation; points) experiment.

sizes of the droplets in the aerosol cloud formed will be not larger than 1 mm. On the basis of analysis of the data for We = 10, presented in Fig. 4, the dependence of the distance traveled by a water mass on its initial size has been obtained (Fig. 5). This dependence can be used for determining the conditions of breakage of water masses and formation of an aerosol cloud with droplets of required sizes. In the calculations, it was assumed that a water mass is broken down at We = 10. In real practice, such processes can proceed at We = 8–12.

In Fig. 6, the times of suppression of the thermal decomposition of birch leaves in a model fire hotbed of height $h_{FCM} \approx 40$ mm and area $S_{FCM} \approx 0.002$ m^2 under the action of aerosol flows with droplets of different sizes are presented. It is seen that, when the sizes of the droplets increase from 60 to 200 μm at a constant specific density of spraying of a fire ($\xi = 0.02$ L/(m^2·s)), the time of its suppression increases by almost 50 s. This allows the conclusion that the use of an aerosol flow with large water droplets for the suppression of the thermal decomposition of FCMs is not always reasonable. Since the time of suppression of the thermal decomposition of a FCM with the use of large water droplets is larger than the time of suppression of the thermal decomposition of this FCM with the use of small water droplets, the volume of water required in the case of spraying of large droplets is much larger than that in the case of spraying of small droplets. As is seen from Fig. 6, the time of suppression of the thermal decomposition of a FCM decreases markedly with decrease in the sizes of the droplets used for this purpose, except when $R_d \approx 0.06$ mm. In this case, t_s is somewhat larger than that in the case where $R_d \approx 0.11$ mm. This result can be explained on the basis of the data of a high-speed video recording of the suppression of the thermal decomposition of a FCM, which clearly show that droplets of size $R_d \approx 0.06$ mm practically completely evaporate before they come in contact with the surface of the FCM. Because of this, the effect of the endothermic phase transition on the FCM surface is somewhat weaker, as compared to that of larger droplets evaporating in this region, which is evidenced by the decrease in the time t_s.

The dependences shown in Figs. 4–6 can be used for forecasting optimum parameters of the suppression of the thermal decomposition of a FCM, in particular, the minimum volume of a water mass required for this purpose and the height from which it should be thrown down to provide the minimum time of suppression of a fire. For example, it is seen from Fig. 5 that, after a water mass thrown down from a height has traveled a distance of 40 m, it is transformed into a cloud of droplets with sizes smaller than 1.5 mm. The fall of a water mass from a height of 100 m results in the formation of a cloud with droplets of average radius $R_d < 0.75$ mm. In this case, in order that a fire be effectively suppressed, it is necessary that the time of movement of droplets to the ground be 120–150 s (Fig. 4). A cloud of water droplets with these characteristics can be formed in the case where several portions of an extinguishing compound are thrown down successively to a hotbed of fire. It may be suggested that, if the required volume of this compound is provided, the fire will be suppressed in a short time. Such a volume of the extinguishing compound can be determined by the formula $V_s = \xi S_{FCM} t_s$.

The results obtained allow one to forecast the height of throw-down of a water agglomerate necessary for the formation of a cloud with droplets of required size, the characteristic time of suppression t_s of a fire, and the volume of water V_s necessary for this purpose. An analysis of these data has shown that, to provide minimum values of the parameters t_s and V_s, it is wise to throw down a water agglomerate from a height not smaller than 100 m, because, in this case, the sizes of the droplets near the surface of a FCM will be substantially smaller than 0.5 mm (Figs. 5 and 6). It was established that, with increase in the size of the droplets in an aerosol flow, the time of suppression of the thermal decomposition reaction of a FCM increases, which leads to an increase in the volume of water necessary for the suppression of a fire. This peculiarity is due to the different mechanisms of suppression of a forest fire by aerosol clouds with droplets of different sizes. In the case where a water flow with droplets of size $R_d \approx 1.5$ mm is sprayed over a thermally decomposing FCM, within a small interval of time water droplets accumulate on the FCM surface, penetrate into its pores, and, in so doing, decrease the temperature of the FCM. Droplets of smaller sizes evaporate most often in the gas phase and do not reach the surface of a FCM (only a small portion of the water used comes in contact with the FCM surface). In this case, the mechanism of suppression of the thermal decomposition of a FCM is based on the formation of a buffer vapor layer at the FCM surface, which aids in the cooling of the near-surface layer of the FCM and the products of its thermal decomposition and prevents the mixing of them with the oxidizer. Under these conditions, the flame burning of a FCM is terminated for a fairly short time because the rate of pyrolysis of this material decreases due to the substantial decrease in its temperature. Our experiments have shown that it is more advantageous to use a finely dispersed droplet flow for the extinguishing of a forest fire because, in this case, the time of suppression of the thermal decomposition of FCMs and the volume of water required for this purpose are smaller compared to the extinguishing of this fire with the use of large water droplets. The main reason for this effect is that the area of evaporation of small droplets is substantially larger compared to that of large droplets and, consequently, the rate of vapor formation is also larger in the case of use of small droplets for the suppression of a fire. This endothermic phase transition mainly determines the temperature of the near-surface layer of a FCM.

In the process of movement of a water mass through a counterflow of the high-temperature products of combustion of a FCM, the droplets in it can collide, coagulate, and break down [22]. Our experimental investigations have shown that the coagulation of droplets in a water mass thrown down from a height to a fire hotbed can proceed in the three regimes: 1) the droplets moving in the wake of the combustion products catch up and coagulate with the droplets moving ahead of them; 2) because of the drag force of the gas flow, the droplets in the water mass change direction of their movement to the opposite one and coagulate with the droplets following them; 3) the droplets moving in parallel at any distance from each other coagulate in the case where the static pressure between them decreases and evaporate as a result of the phase transformations. It was established that the collisions between the droplets in a water mass are probabilistic in character. Therefore, using dependences and diagrams presented in [22], one can forecast the dispersivity of a flow of water droplets falling free in air and moving in a counterflow of high-temperature gases. The influence of this parameter on the characteristics of the suppression of a fire with the use of water masses thrown down from a height is very difficult to estimate. In the first approximation, it is appropriate to determine the average sizes of the droplets in an aerosol cloud, formed in the process of transformation and breakage of a water mass, and correct, with the use of data from [22], the estimates obtained for corresponding conditions of throw-down of water. Moreover, it is necessary to take into account the fact that the droplets moving in a high-temperature counterflow not only collide with each other [22] but are also carried away [23]. In this case, the minimum possible size of the droplets that can be carried away is $R_d = 0.08$–0.1 mm [23]. Therefore, the indicated peculiarity should be taken into account in determining the height of throw-down of a water mass for suppression of a fire and the volume of water necessary for this purpose with the use of data presented in Figs. 5 and 6.

Conclusions. Our experimental investigations allowed us to determine the characteristic times of suppression of forest fires of different areas and the volumes of water masses with droplets of different sizes required for this purpose. It was shown that the thermal decomposition of the typical FCMs is most effectively suppressed with the use of a finely-dispersed aerosol. It was established that the main reason for the termination of the pyrolysis of a FCM is the intensive vapor formation at its surface, substantially decreasing the temperature of the near surface layer of the FCM, with the result that a buffer zone is formed between the oxidizer and the products of thermal decomposition of the FCM. An analysis of the data obtained allowed us to construct an algorithm for forecasting, in the first approximation, the conditions necessary for the efficient suppression of the thermal decomposition of a FCM with the use of large agglomerates of water. In this case, the parameters of throw-down of a water mass from a height (the value of this height and the volume of the water) should be decided on the basis of experimental data on the suppression of model fire hotbeds of FCMs.

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NOTATION

h_{FCM}, height of a model hotbed, m; R_d, radius of a water droplet, mm; S_{FCM}, surface area of a FCM, m^2; T_{FCM}, temperature of the thermal decomposition of a FCM, K; t_b, time of burn-out of a FCM without recourse to water, s; t_s, time of suppression of a fire, s; U_d, velocity of movement of aerosol droplets, m/s; V_d, volume of a water droplet, liter; V_s, volume of the water expended for the suppression of a fire, liter; V_e, excess water in a pan, L; We, Weber number; γ_{FCM}, moisture content of a FCM, %; γ_d, volume concentration of droplets in a flow, droplet/m^3; μ_w, specific flow rate of the water sprayed by an atomizer, L/s; ξ, specific density of spraying, L/(m^3·s). Subscripts: b, burning; d, droplet; e, excess; w, water.

REFERENCES

1. A. Dimitrakopoulos, C. Gogi, G. Stamatelos, and I. Mitsopoulos, Statistical analysis of the fire environment of large forest fires (>1000 ha) in Greece, *Pol. J. Environ. Stud.*, **20**, 327–332 (2011).
2. F. X. Catry, F. C. Rego, F. Moreira, and F. Bacao, Characterizing and modelling the spatial patterns of wildfire ignitions i n Portugal: Fire initiation and resulting burned area, *1st Int. Conf. on Modelling, Monitoring, and Management of Forest Fires*, 17–18 September 2008, Spain (2008), Vol. 119, pp. 213–221.
3. D. H. Klyde, D. J. Alvarez, P. C. Schulze, T. H. Cox, and M. Dickerson, Limited handling qualities assessment of very large aerial tankers for the wildfire suppression mission, *AIAA Atm. Flight Mech. Conf.*, 2–5 August 2010, Canada (2010), Code 97625.
4. L. Merino, F. Caballero, J. R. Martínez-De-Dios, I. Maza, and A. Ollero, An unmanned aircraft system for automatic forest fire monitoring and measurement, *J. Intell. Robot. Syst.*, **65**, Issues 1–4, 533–548 (2012).
5. A. Yu. Pidzhakov, F. N. Reshetskii, and O. V. Gavrilova, Use of aircrafts of the Ministry of Emergency Situations of Russian for suppression of forest fires, *Vestn. Sankt-Peterb. Univ. Gos. Protivop. Sluzhby MChS Rossii*, No. 1, 68–71 (2011).
6. E. A. Moskvilin, Use of aircrafts for suppression of forest fires, *Pozhar. Bezopasnost'*, No. 1, 89–92 (2009).
7. I. R. Khasanov, V. S. Gorshkov, and E. A. Moskvilin, Parameters of the process of suppression of forest fires in the case of supply of water by aircrafts, in: *Proc. Int. Conf. "Forest and Steppe Fires: Appearance, Propagation, Suppression, and Subsequences for the Environment*," 25–29 September 2001, Irkutsk (2001), pp. 157–158.
8. I. R. Khasanov and E. A. Moskvilin, Aviation methods for suppression of large forest fires, in: *Proc. XV Sci.-Pract. Conf. "Problems of Combustion and Suppression of Fires at the Turn of the Century*," Moscow (1999), Part 1, pp. 300–301.

9. A. O. Zhdanova, G. V. Kuznetsov, and P. A. Strizhak, Numerical investigation of physicochemical processes occurring during water evaporation in the surface layer pores of a forest combustible materials, *J. Eng. Phys. Thermophys*., **87**, No. 4, 773–781 (2014).
10. R. S. Volkov, A. O. Zhdanova, O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, Mechanism of liquid drop deformation in subsonic motion in a gaseous medium, *J. Eng. Phys. Thermophys*., **87**, No. 6, 1351–1361 (2014).
11. A. O. Zhdanova, G. V. Kuznetsov, and P. A. Strizhak, Evaporation of water in the process of movement of its large masses through a high-temperature gas medium, *J. Eng. Phys. Thermophys*., **88**, No. 5, 1145–1153 (2015).
12. J. Westerweel, Fundamentals of digital particle image velocimetry, *Meas. Sci. Technol*., **8**, 1379–1392 (1997).
13. S. Dehaeck, H. Van Parys, A. Hubin, and J. P. A. J. Van Beeck, Laser marked shadowgraphy: a novel optical planar technique for the study of microbubbles and droplets, *Exp. Fluids*, **47**, No. 2, 333–341 (2009).
14. A. M. Grishin, *Mathematical Models of Forest Fires* [in Russian], Izd. Tomsk. Gos. Univ., Tomsk (1981).
15. S. A. Loshchilov, *Influence of the Thermokinetic Parameters of the Pyrolysis and the Two-Layerage of Forest Combustible Materials on the Processes of Propagation of Forest Fires*, Candidate's Dissertation (in Physics and Mathematics), R. E. Alekseeev Nizhegor. Gos. Tekh. Univ., Nizhnii Novgorod (2013).
16. A. N. Subbotin, Mathematical model of propagation of a creeping forest fire over a litter or a layer of waste conifer needles, *Pozhar. Bezopasnost'*, No. 1, 109–116 (2008).
17. A. M. Grishin, V. P. Zima, V. T. Kuznetsov, and A. I. Skorik, Ignition of forest combustible materials by a radiant energy flow, *Fiz, Goreniya Vzryva*, **38**, No. 1, 30–35 (2002).
18. A. M. Grishin, V. V. Reino, V. M. Sazanovich, and R. Sh. Tsvyk, Some results of experimental investigations on the combustion of forest combustible materials, *Izv. Vyssh. Ucheb. Zaved*., *Fizika*, **52**, No. 12, 28–37 (2009).
19. R. M. Aseeva, B. B. Serkov, and A. B. Sivenkov, Combustion and fire hazard of wood, *Pozharovzryvobezopasnost'*, **21**, No. 1, 19–32 (2012).
20. M. B. Gonchikzhapov, A. A. Paletskii, and O. P. Korobeinichev, Kinetics of the pyrolysis of forest combustible materials in an inert/oxidizing medium at large and small rates of their heating, *Sibbezopasnost'-Spassib*., No. 1, 38–44 (2012).
21. R. S. Volkov, G. V. Kuznetsov, P. A. Kuibin, and P. A. Strizhak, Weber numbers for the stages of transformation of water agglomerates in their free fall in air, *Pis'ma Zh. Tekh. Fiz*., **41**, No. 20, 103–110 (2015).
22. D. V. Antonov, R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, Experimental study of the effects of collision of water droplets in a flow of high-temperature gases, *J. Eng. Phys. Thermophys*., **89**, No. 1, 100–111 (2016).
23. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, Influence of the initial parameters of a sprayed water on the characteristics of its movement through a counterflow of high-temperature gases, *Zh. Tekh. Fiz*., **84**, No. 7, 15–23 (2014).