

MOVEMENT OF WATER DROPS IN A FOREST FUEL LAYER IN THE COURSE OF ITS THERMAL DECOMPOSITION

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In this paper, we conducted an experimental investigation on water droplets gravitating in a layer of typical forest fuel (as illustrated by pine needle litter) in the course of its thermal decomposition. We used a high-speed (200 fps) video recording system, Tema Automotive software with continuous tracking of a moving object as well as a set of low-inertia (no more than 0.1 s) thermocouples. Similar experiments were performed at moderate temperatures (below the onset temperature of forest fuel pyrolysis, i.e. about 300 K). Two approaches were used: continuous tracking of a moving water droplet using high-speed video recording; and registration of a droplet path using the readings of thermocouples placed at different levels in a forest fuel (FF) layer. We determined the typical depths of an FF layer that water droplets reach with the initial volume of these droplets ranging from 90 to 900 μL . The typical velocities of water droplets were calculated at different depths of the FF layer. We also determined the share of the mass of water spent in an FF layer on evaporation and cooling of the material down to the temperatures below those of thermal decomposition. Finally, we identified the physical processes influencing water droplets moving through the layers of forest fuel heated up to the high temperatures similar to those of thermal decomposition.

Keywords: *forest fuel layer, thermal decomposition, pyrolysis, water droplet, progress, penetration depth.*

1. Introduction

Forest fire fighting by means of aircraft predominantly involves dropping large masses of water (up to 30–50 tons at a time) onto the fire zone [1–3]. Wildfires are suppressed using three effects of water on the processes taking place in burning forest fuel (FF) [4]: (a) it reduces the temperature of the flame and the reacting material as a result of rapid evaporation; (b) it forms a vapor cloud ousting the air from the area of interaction with fuel (gaseous products of thermal decomposition of forest fuel); and (c) it suppresses forest fuel pyrolysis. Under a strong wind, which is typical of forest fires, the first two methods may be insufficiently effective. The third one, however, provides flame suppression under any conditions. Therefore, it is of the greatest interest to investigate the processes taking place in forest fuel heated up to high temperatures when the fuel interacts with water droplets. No findings have been published so far of experimental research into the processes typical of heat and mass transfer in a porous structure of thermally decomposing forest fuel, when water droplets move through a layer of this material heated up to the temperatures significantly exceeding the onset temperature of FF thermal decomposition.

To substantiate the intensity of water supply into a layer of the burning forest fuel sufficient to suppress its thermal decomposition, the knowledge is necessary on water droplet movement through the porous structure of forest fuel in the course of its rapid thermal decomposition. We have no record

of published results of any experimental research into the water droplet movement in an FF layer (at both moderate temperatures and under conditions of its thermal decomposition).

The most widespread forest fuels under study by researchers and specialists of fire-fighting services are leaves, pine needles, and twigs [5, 6]. The analysis has shown that fuel density may range from 10 kg/m^3 to 55 kg/m^3 and fuel thickness, from 30 mm to 100 mm [5, 6]. Since the movement of water drops through the fuel bed is hard to trace, it is useful to experiment with individual water droplets by varying their initial size.

The aim of this work is to use our experimental research findings to establish how water droplets move in a porous structure of forest fuel at the stage of thermal decomposition.

2. Experimental methods and procedures

To create a model forest fuel combustion source (see fig. 1), we used a thin-walled quartz glass cylinder (inner diameter $d_f \approx 100 \text{ mm}$, height $h_f \approx 120 \text{ mm}$) filled with forest fuel material (pine needle litter). The cylinder-shaped pine needles were on average 0.7–1 mm in diameter and 30–50 mm in length. The fuel bed thickness varied between 40 mm and 120 mm in the experimental cylinder (in accordance with the thickness of the fuel bed in actual woodlands [5, 6]).

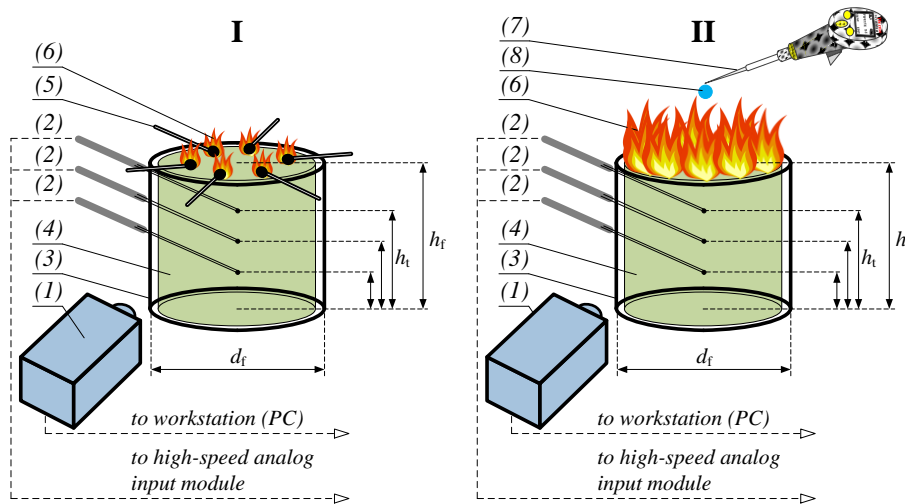


Figure 1. Scheme of an experimental setup before (I) and during (II) the experiment: high-speed video camera (1); three low-inertia thermocouples (2); quartz glass cylinder (3); forest fuel (4); piezo igniters (5); flame (6); dispenser (7); water droplet (8)

We chose pine needle litter, because this type of forest fuel generally enables us to record the movement of both a single water droplet and a group thereof through a layered structure (continuous tracking is provided). For birch leaves or aspen branchlets, for example, an accurate portrayal of how a water droplet moves is complicated, because forest fuel elements block the view despite specialized illumination of the fuel bed. The density and moisture content of forest fuel sample were taken as average of those actually possible in forest fires. In particular, the bulk density amounted to $30\text{--}35 \text{ kg/m}^3$ (calculated using the following formula: $\rho_f = m_{f0} / (h_f \cdot S_f)$, kg/m^3 , where $S_f = \pi \cdot (d_f/2)^2$), and the moisture content, to $7\text{--}10\%$ (calculated by the formula $\gamma_f = (m_{fw} - m_{fd}) / m_{fw} \cdot 100$, %). Fuel load (m_s) was calculated by the formula $m_s = \rho_s \cdot \alpha_s \cdot h_f$, where $\rho_s \cdot \alpha_s = \rho_f$ and amounted to $3.6\text{--}4.2 \text{ kg/m}^2$.

To determine the moisture content of a forest fuel sample, it was dried for three-five days at a temperature of about 300 K. Immediately before a series of experiments, we determined the moisture content of the material by thermal drying. For this, the forest fuel under study was weighed and then placed into a drying oven for two-three hours at a temperature of about 375 K. After drying, the

sample was cooled down (during 30 s) and re-weighed. We used a ViBRA HT 84RCE weighing system (the minimum and maximum weigh is 0.01 g and 80 g with an accuracy of 0.0001 g).

The results of the experiments determined the following: the velocities (U_f) of droplets going through a layer of forest fuel; the depth (h) of droplet penetration; the corresponding droplet movement times in a forest material sample (t). We varied the volumes of water droplets (V_d) in the experiments within the range of 90–900 μL (in accordance with changes in the initial radii from 2.7 mm to 5.9 mm) using an electronic dispenser (the minimum and maximum dosage volumes were 1 μL and 1.000 μL , with variation accuracy of 0.1 μL). The initial velocity of droplets did not exceed 0.5 m/s (the same as that of their release by the dispenser). During the experiments, 1 to 3 water droplets were injected into the sublayer of forest fuel. In the experiments with several droplets injected, the time delay between their injection was approx. 1 s.

The experiments had two stages. At the first stage, water droplets were placed on the surface of a non-pyrolyzed forest fuel sample. The second stage involved identical experiments with thermally decomposing forest fuel. In this case, the FF thermal decomposition was initiated using several piezo igniters. These ignited the forest fuel in the upper part of the sample. The flame covered the whole surface of the FF sample, and the combustion front started moving deeper into the sample. Then we waited for 15–20 s until the temperature throughout the FF layer exceeded the onset temperature of the thermal decomposition, 400 K. When that happened, it meant that the forest fuel was decomposing throughout its thickness. If the readings of at least one of the three thermocouples did not reach the said temperature, the forest fuel was considered to be burning unstably. In that case, the experimental results were excluded from further investigation.

The depth h of droplet penetration and the corresponding times t were measured using two registration schemes. The first one employed a National Instruments NI 9213 analog input module and three type K thermocouples (temperature range 223–1473 K, accuracy ± 3 K, heat retention no more than 0.1 s) placed in series in a forest fuel layer (see fig. 1). Their readings were transmitted to a personal computer (PC) in the form of temperature curves continuously changing over time (with an accuracy of 1 s). When a water droplet landed on a sensor (or passed close to it), a thermocouple recorded a significant drop in temperature (this moment signaled that the droplet reached the corresponding section of the forest fuel). The experiments involved the alteration of distances between thermocouples (from 5 to 50 mm) and registration of the times, in which the droplets covered these distances. We only used this scheme in the experiments with pyrolyzing forest fuel.

The thermocouples were held fixed at a particular distance by means of a specialized positioning system. Then the whole framework with the thermocouples moved closer to the FF sample. Due to a smooth and accurate motion of the positioning mechanism with a step size of 0.5 mm, it stopped when the thermocouple junctions reached the axis of symmetry of the cylinder with the FF sample.

The second scheme of determining $h(t)$ implied the calculation of the distances h covered by water droplets and the corresponding times t as part of the analysis of the video recordings. A high-speed digital CMOS video camera Phantom V411 (recording frequency up to 10^5 fps, maximum resolution 1280×1280 pixels) recorded the process with a frequency of 200 fps. The forest fuel layer was lit using a specialized illumination system based on a LED matrix.

Tema Automotive software [7, 8] was used for continuous tracking of the moving droplet. First, we identified the boundaries of the droplet using the Circular Symmetry algorithm. At the second stage, we used the Correlation algorithm to automatically (by means of Auto Select procedure) assign the location of the extreme points of the droplet as well as its center of mass. After that, as the droplet moved through the FF bed, the software provided continuous tracking of the points identified at the second stage. We also plotted their trajectories. At the same time, we determined the velocities of the extreme points and center of mass of the droplet in a fuel bed by means of 2D Pixel Velocity

software. At the end of the processing, the velocities of all the points were averaged for identical time segments. The average droplet velocity in a fuel bed was measured as well.

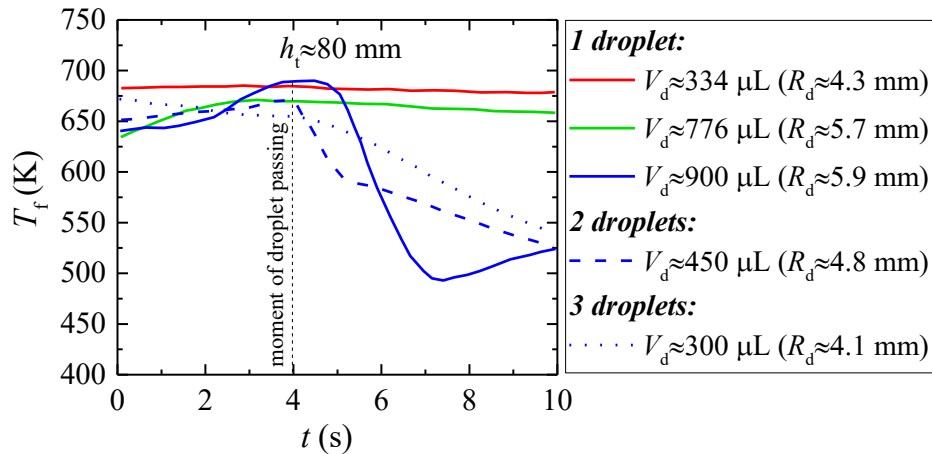
All the experiments were performed for two cases:

- when droplets moved through a forest fuel layer untouched by thermal decomposition or flame burning; and
- when droplets moved through a forest fuel layer in the course of its rapid thermal decomposition and flame burning of gaseous products of forest fuel pyrolysis.

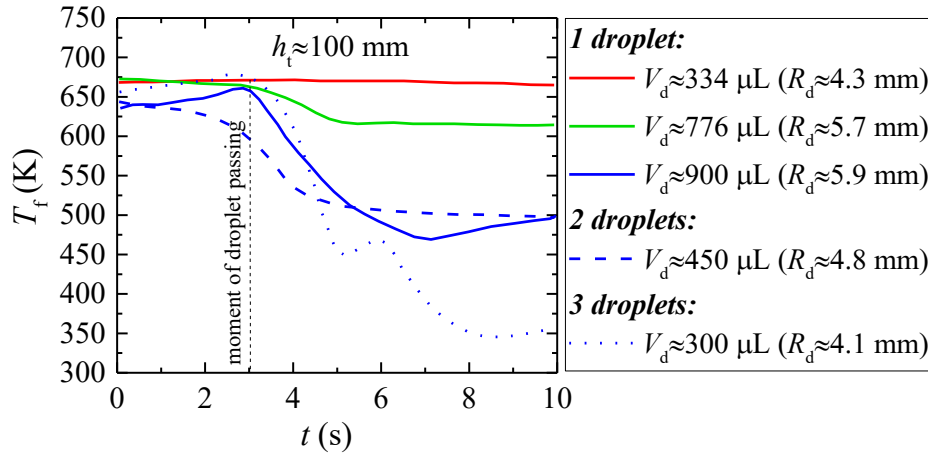
The $h(t)$ curves enabled us to determine the velocities of a droplet moving through a forest fuel layer at any distinctive section of its path. When analyzing the research findings, we used the so-called instantaneous velocities U_f calculated for short sections (usually 5–10 mm) of the droplet path.

In thermocouple measurements, the criterion showing that a moving droplet had reached the surface of one of the three thermocouples was a rapid decrease in the temperature they were measuring (in particular, the first approximation controlled if the $dT_f/dt > 10$ K/s condition held). The experiments with a system of high-speed video recording determined the ranges of datum velocities of the droplet movement U_f and estimated their corresponding penetration depths h . Experiments with thermocouples then revised these estimated values. Figure 2 quite clearly shows a significant decline in temperature in different sections along the height of an FF sample due to a water droplet penetrating into the reacting layer. At the same time, from the experiments with small droplets we can see that only the first (upper) thermocouple reacts to their movement. This result shows that smaller-size droplets do not reach the lower depths of the pyrolyzing forest fuel. In addition, it is clearly visible that a rise in the size of the droplets does not only increase the depth of their penetration into forest fuel but also the difference in the temperature of the layer before and after a droplet passes through it (see fig. 2).

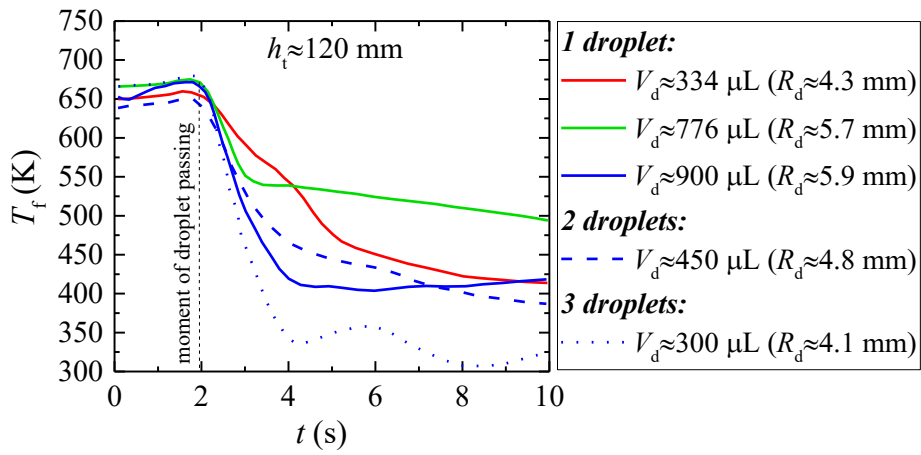
Figure 2 shows that we have established the following. If we do not change the initial volume ($V_d \approx 900 \mu\text{L}$) but split the droplet two or more times, this provides the best result: minimum temperatures of the pyrolyzing FF and maximum duration of reduced temperature if several droplets are supplied to the fuel bed surface. The best temperature reduction was in the near-surface layer of the FF (see fig. 2, b,c).



(a)



(b)



(c)

Figure 2. Curves of forest fuel temperatures when a single water droplet passes through it with thermocouples placed at different distances from the base of the sublayer: 80 mm (a), 100 mm (b), and 120 mm (c); the initial volumes of the droplets corresponded to their radii: $V_d \approx 300 \mu\text{L} - R_d \approx 4.1 \text{ mm}$; $V_d \approx 334 \mu\text{L} - R_d \approx 4.3 \text{ mm}$; $V_d \approx 450 \mu\text{L} - R_d \approx 4.8 \text{ mm}$; $V_d \approx 776 \mu\text{L} - R_d \approx 5.7 \text{ mm}$; $V_d \approx 900 \mu\text{L} - R_d \approx 5.9 \text{ mm}$

Figure 3 presents typical frames of a high-speed video recording illustrating the position of a water droplet in a forest fuel sample, instantaneous values of velocity and characteristic periods after the droplet reaches the sample surface.

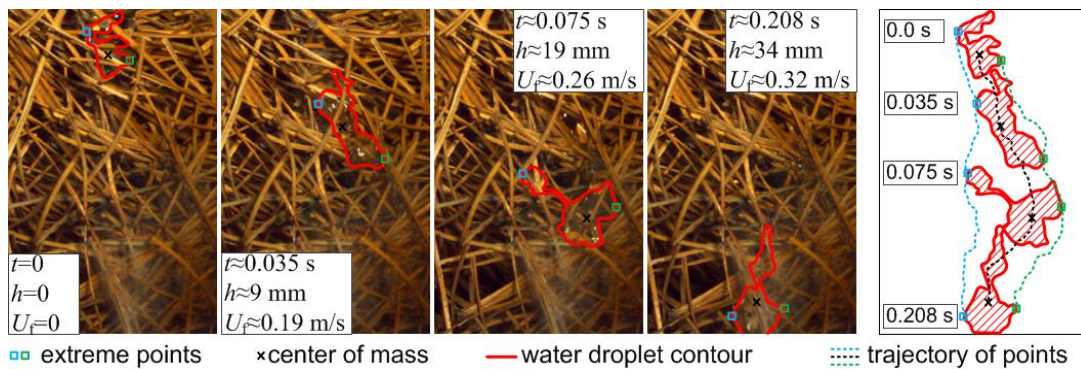


Figure 3. Video recordings of a water droplet ($V_d \approx 800 \mu\text{L} - R_d \approx 5.7 \text{ mm}$) passing through a layer of forest fuel at moderate temperatures (300 K), i.e. without the pyrolysis of the fuel material

Random errors of the experiments were determined similarly to experiments [9, 10] and were as follows relative to the mean values under identical conditions: 15% for h , and 18% for U_f . To provide an acceptable accuracy, we performed 8–12 experiments under identical conditions. If the errors exceeded these values, the experimental results were disregarded in the subsequent consideration. It is important to note that the key disagreements between the results of experiments to determine $h(t)$ and $U_f(t)$ stem from the forest fuel structure. In particular, due to the porosity of the forest fuel, water droplets chose different paths to move through a layer of the material. Due to the random disposition of needles, the droplets followed the paths that fluctuated within the range of 3–15 mm along the transverse coordinate from one experiment to another. The allowable deviation was 5 mm, since when it exceeded this value, the readings of thermocouples differed dozens of degrees from mean values.

The mass of water was also measured using ViBRA HT 84RCE scales after the droplets passed through the forest fuel layer. The droplets were weighed before putting them down on the forest fuel sample (m_{d0}) and after passing through it (m_{de}) under moderate temperatures and in the course of thermal decomposition. For this purpose, a receiver (a round plate with the diameter d_r) made of 1-mm thick metal was placed under the cylinder with a sample. The dispenser then collected a droplet from the receiver by means of an inverse function. A droplet was then placed on the scales and weighed. The random errors of m_{de} did not exceed 5%. Six to ten experiments were performed to achieve this reasonable accuracy.

3. Results and discussion

The main objective function in the experiments was chosen to be the recording of the distances covered by a droplet in a forest fuel layer (progress depth h) and velocity of its movement U_f . The initial dimensions (volumes) of droplets and the temperature of the forest fuel were taken as the key significant factors of the processes under study. Figures 4–7 show the results of the experiments with droplets having the following volume-radius ratios: $V_d \approx 90 \mu\text{L} - R_d \approx 2.8 \text{ mm}$; $V_d \approx 200 \mu\text{L} - R_d \approx 3.6 \text{ mm}$; $V_d \approx 800 \mu\text{L} - R_d \approx 5.7 \text{ mm}$.

Figure 4 (thermocouple measurements) and Figure 5 (high-speed video recording with continuous tracking) present experimental dependences of the penetration depth (h) of droplets with three different sizes into forest fuel. The correlation between h and the initial dimensions (volume) of droplets is evident. The larger the latter, the greater distances a droplet covers under gravity through an aggregate of randomly positioned needles. Note that the high-temperature pyrolysis of forest fuel has virtually no effect on the depth of droplet penetration into forest fuel. This most probably stems from high porosity of this forest fuel (relative porosity of pine needle litter may reach 70–90%). Gaseous products formed during pyrolysis and moving in the opposite direction to the droplet almost do not slow down its movement. We can also conclude that the influence of bulk forces is more significant than that of droplet motion resistance forces. Droplets of 800 μL pass through the whole forest fuel layer (up to 60 mm thick) losing up to 20–30% of its mass. The analysis of the dependences shown in Figures 4 and 5 confirms the assumption that the velocities of large droplets are much higher than those of small droplets. The latter are decelerated by the elements of forest fuel structure, whose typical transverse and longitudinal dimensions are comparable with the typical diameters of relatively small droplets (under 3 mm).

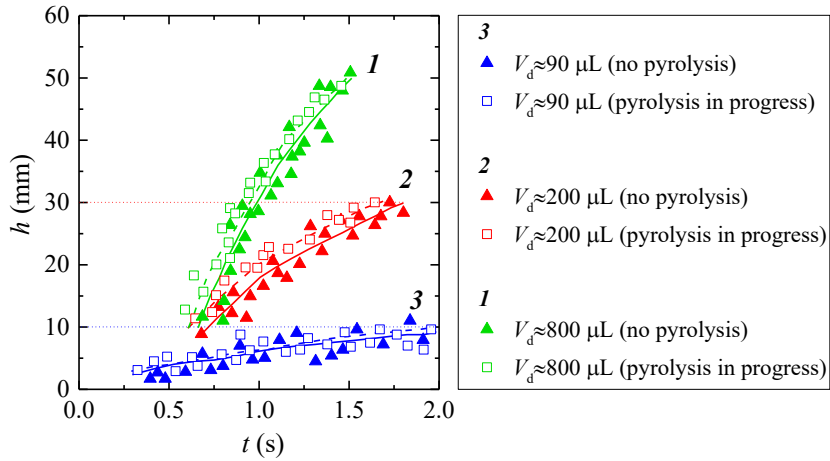


Figure 4. Dependences of depth of droplet penetration in an FF layer on the time (without FF pyrolysis and during FF thermal decomposition) obtained using the first registration scheme (thermocouple measurements). Points show the results for a series of experiments.

It follows from the obtained results that a certain not very large (most likely less than 4–5 mm) typical size of the droplets provides the most effective suppression of the thermal decomposition of forest fuel. Large droplets sized more than 5 mm will pass through the whole layer of the decomposing forest fuel and penetrate the structure of the material that the pyrolysis front has not reached. Just a fraction of the droplet mass will evaporate when moving through the area of high temperatures (above the onset temperature of thermal decomposition). As to medium-sized and especially small-sized droplets (less than 1 mm), these will evaporate completely in the area of forest fuel pyrolysis. The latter provides the maximum temperature reduction in this area and stops the thermal decomposition of forest fuel. Thus, small droplets provide the most efficient water consumption to reduce the temperature in a layer of thermally decomposing forest fuel.

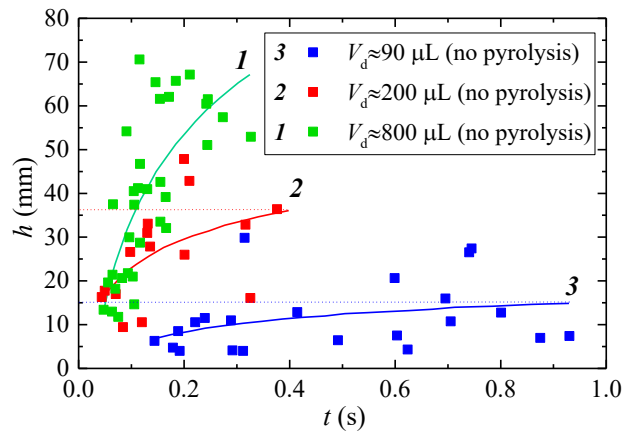


Figure 5. Dependence of depth of droplet penetration in an FF layer on the time (without FF pyrolysis) obtained using the second registration scheme (high-speed video recording). Points show the results for a series of experiments.

Generally, the correspondence of nature and inclination of the curves in Figures 4 and 5 (plotted using different registration schemes) is satisfactory. The difference in dependences $h(t)$ in Figures 4 and 5 is due to a longer polling interval of thermal voltage converters, which was 1 s in the experiments. If we take into account the thermal lag of thermocouples, which may reach 0.1 s, we will find that the error of time determination in the first registration scheme may even be somewhat higher

than 1 s. The difference of limit (maximum possible) distances covered by the droplets in a forest fuel layer (horizontal dotted lines in Figures 4 and 5) is negligible and stems from the nature of their movement. In most cases, water droplets take complicated paths in a forest fuel layer due to different structures of layers formed by randomly located needles. The greater distance a droplet covers in a forest fuel layer, the greater deviation on a transverse coordinate it acquires from its initial direction. Experiments with high-speed video recording of the thermal decomposition of forest fuel were limited by high smoke emission due to the emerging pyrolysis products. However, if we analyze Figures 4 and 5, we can conclude that the times the droplets need to pass through the decomposing forest fuel will be somewhat lower (no more than 10%) than the corresponding lines for the experiments without pyrolysis.

Figure 6 provides the calculated values of the instantaneous velocity of a water droplet moving through forest fuel layers.

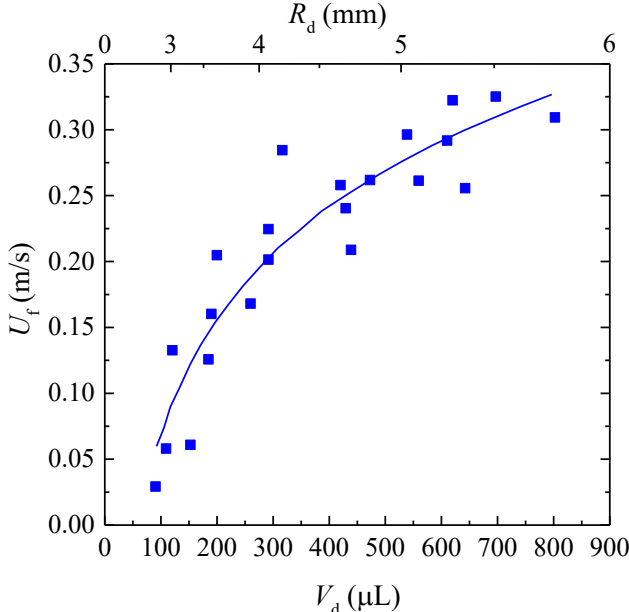


Figure 6. Dependence of instantaneous velocities of water droplets passing through a forest fuel layer on the initial volumes and radii of these droplets

The analysis of distributions $U_f=f(V_d)$, $U_f=f(R_d)$, and $U_f=f(h)$ in Figures 6 and 7 shows that medium-sized droplets ($R_d \approx 3$ mm) pass through a forest fuel layer, say, 10 mm thick, in no more than 0.3 s. Over such a short term, a water droplet will only lose no more than 10% of its mass if the forest fuel temperature ranges from 400 K to 900 K (the range corresponding to the thermal decomposition of the latter) judging by the results of experiments [9, 10]. That is, with a typical droplet size of over 3 mm, most water will pass through the forest fuel heated up to high temperatures into its cold layers.

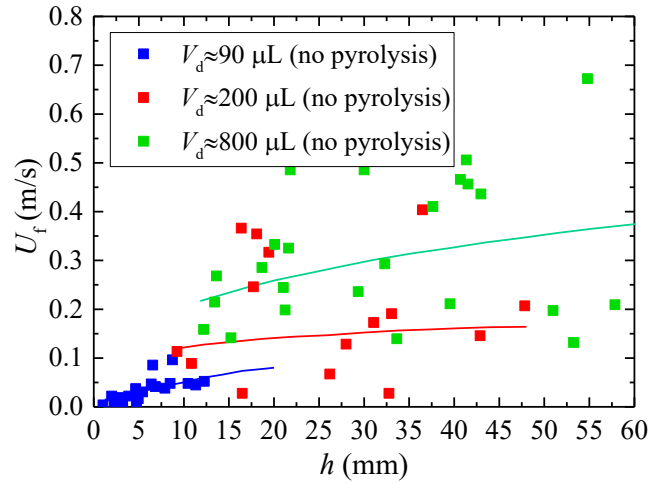
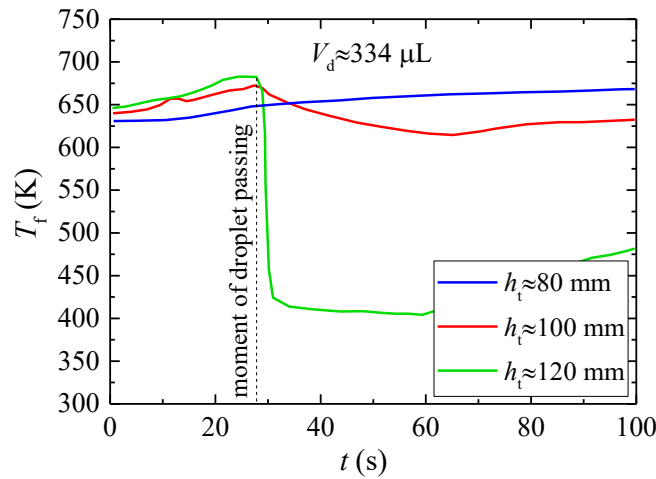
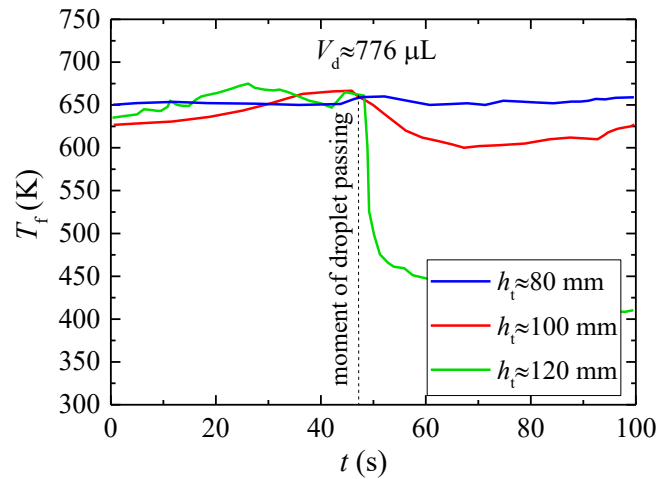


Figure 7. Instantaneous velocities of water droplets moving through a forest fuel layer (for three different initial droplet volumes)

Figure 8 provides typical curves of temperature in pyrolyzing forest fuel after injecting isolated water droplets of different initial volumes. These are simultaneous readings from three thermocouples positioned at different levels in a layer of thermally decomposing forest fuel.



(a)



(b)

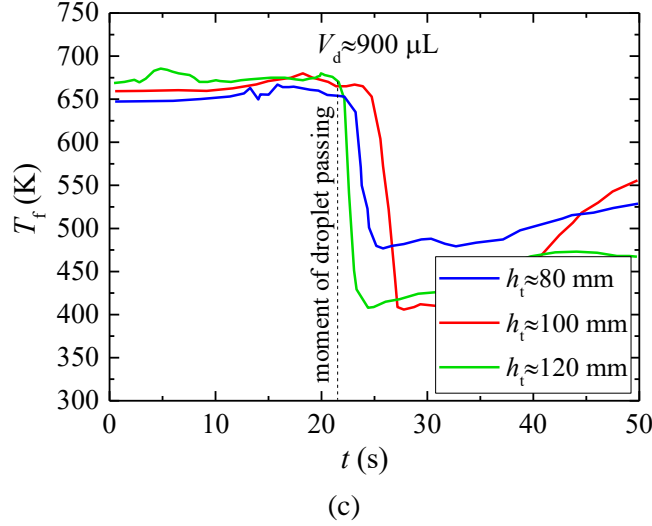


Figure 8. Temperature curves in a forest fuel layer when a single water droplet of different initial volumes passes through it: (a) – $V_d \approx 334 \mu\text{L}$, (b) – $V_d \approx 776 \mu\text{L}$, (c) – $V_d \approx 900 \mu\text{L}$

You can clearly see an almost instantaneous drop in the temperature of a forest fuel layer in the immediate vicinity of the water droplet path. The readings of all the three thermocouples (large droplets in Figure 8c) change with a time lag of no more than 1–3 s relative to one another. These times are what characterizes the durations of droplets passing through forest fuel layers where the thermocouples are positioned.

At the same time, there is quite a fast temperature rebound in a forest fuel layer after a large water droplet passes through it. It is clear from Figure 8c that the readings of all the three thermocouples illustrate an increase in T_f . However, the lower R_d and V_d , the longer it takes for T_f to rebound to the values of forest fuel layer temperatures before a water droplet enters it. T_f does not rebound in Figure 8a, because small droplets heat up and evaporate more rapidly than large ones.

Figures 9 and 10 represent the experimentally determined masses of droplets after their passing through a layer of pyrolyzing forest fuel. We used the Δm parameter characterizing a change in the mass when a droplet passes through a forest fuel layer with due consideration of its losses to needle wetting and evaporation: $\Delta m = (m_{d0} - m_{dc}) \cdot 100\%$.

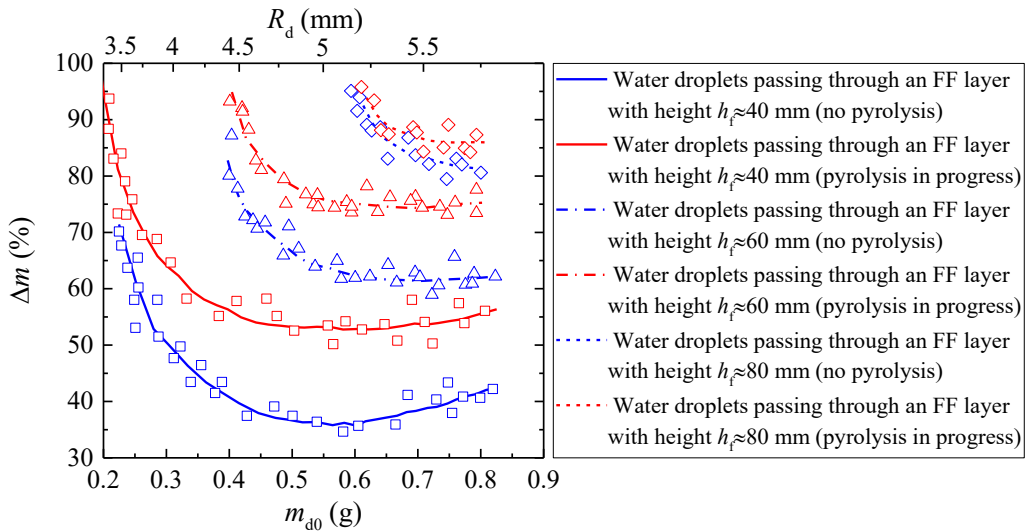


Figure 9. Dependence of Δm on initial droplet mass m_{d0} and radius R_d (at $h_f \approx 40 \text{ mm}$, $h_f \approx 60 \text{ mm}$ and $h_f \approx 80 \text{ mm}$)

Our experiments showed that droplets with a radius of 2.7 mm or less all settled in a forest fuel layer in the experiments with thermal decomposition of the latter and without its heating. The water did not reach the lower part of the sample and it did not leak through to the receiver. Figure 9 provides the results for the droplets with the following initial radii: $R_d \approx 4.3$ mm, $R_d \approx 5.7$ mm, and $R_d \approx 5.9$ mm.

The analysis of the dependences shown in Figure 9 leads to a conclusion that a rise in the droplet size also increases the share of the mass it loses when passing through a forest fuel layer. This result can hardly be considered obvious, since we registered the reverse effect for small droplets ($R_d < 3$ mm): the smaller R_d , the faster the droplets heat up in a layer of pyrolyzing forest fuel and evaporate. In the case of large droplets ($R_d > 5$ mm), the physics of heat and mass transfer processes when these droplets pass through forest fuel undergoes some changes. Consequently, Δm grows when the initial droplet mass m_{d0} increases (see fig. 9). This happens because droplets with a typical volume $V_d \approx 900 \mu\text{L}$ have a greater contact area with forest fuel fragments vs. small droplets. High-speed video recording has shown that the greater the droplet-needles contact area, the more liquid wets them. The area of endothermic phase change increases as well.

Figure 10 represents the dependences of the masses of water droplets after they pass through a forest fuel layer on their initial mass (to illustrate the experimental results and identify the masses of water passing through forest fuel in absolute values). The difference between lines presented in Figures 9 and 10 illustrates the share of water spent on endothermic phase change. It is noteworthy that the greater the initial mass of water, the greater this share. This does not stem as much from the intensification of the vaporization process (on the contrary, the growing water mass in a pyrolyzing forest fuel layer leads to a decline in its temperature and slows down the evaporation) as a growth of the contact area of water and forest fuel structural elements. As a result, the mass of vapors blown in may rise. This leads to a decrease in the pyrolysis rates and forest fuel temperature.

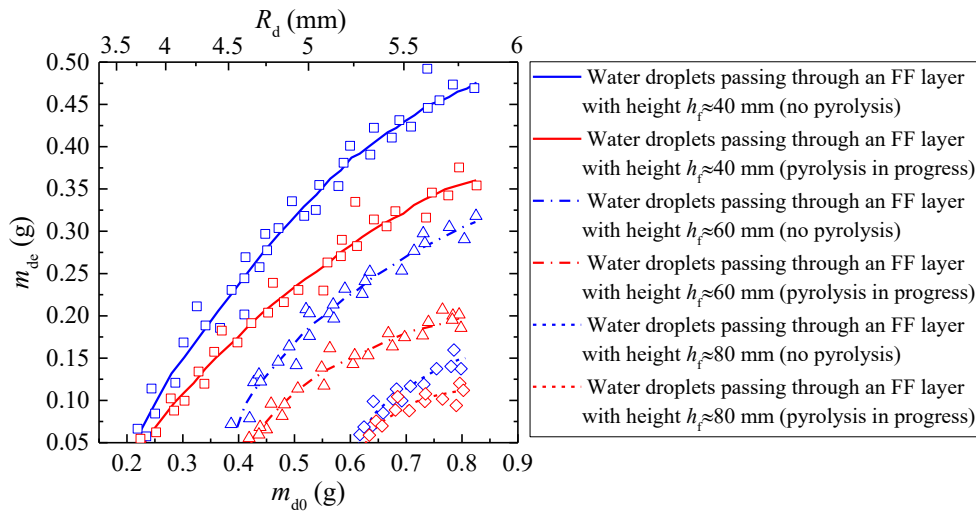


Figure 10. Dependence of the masses of droplets after their passing through a forest fuel layer on their initial mass m_{d0} and radius R_d (at $h_f \approx 40$ mm, $h_f \approx 60$ mm and $h_f \approx 80$ mm)

The obtained results allow us to conclude that with a coarse droplet flow approaching the surface of forest fuel, its thermal decomposition can be suppressed by just filling the whole porous structure of forest fuel with water in the temperature range from moderate (300 K) to the end temperatures of the thermal decomposition of forest fuel. However, the thickness of pine needle litter in both coniferous and mixed forests may reach 3–20 cm [11–15]. Therefore, it is next to impossible to extinguish large burning areas of forest fuel with such thickness using aircraft. Based on the above, we can conclude that it is only possible to suppress the thermal decomposition of pine needle litter during

ground fires by means of fine spraying of water supplied to the forest fuel surface. The droplet size at the forest fuel – flame interface must not exceed 1–2 mm. In this case, as the conducted experiments show, stopping the thermal decomposition of forest fuel and, consequently, fuel cut-off in the burning area becomes a workable objective.

After analyzing and generalizing the results of the conducted experimental research and materials [1–4], we can conclude that fine water spraying is the necessary condition of fire extinguishing.

Conclusions

1. The paths of water droplets passing through an FF layer are broken curves (the droplets follow the path of least resistance). A part of water (up to 15–30%) remains on the needles because of wetting.
2. FF pyrolysis alters its porosity, which grows due to the thermal decomposition of separate needles. Consequently, water passes faster through a pyrolyzing layer. This trend becomes more pronounced with the increasing volume of a droplet.
3. The velocity of water droplets passing through an FF layer increases nonlinearly with a rise in the initial volumes (dimensions) of the droplets under adequate conditions. This most likely stems from the wetting of FF elements by water during the droplet movement.
4. For droplets with a volume $V_d \approx 90 \mu\text{L}$, the limit (longest possible) distances covered were 15 mm; with $V_d \approx 200 \mu\text{L}$, they were 35 mm; and when the volume $V_d \approx 800 \mu\text{L}$, the droplets passed through a 70-mm-thick layer completely.

Acknowledgement

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Nomenclature

- h – distance passed by a water droplet in an FF layer (penetration depth relative to the sample surface) [mm];
- h_f – height of a sublayer with the FF sample [mm];
- h_t – height of the thermocouple placement [mm];
- m_{f0} – initial mass of FF sample [g];
- m_{fd} – mass of FF sample after thermal drying [g];
- m_{fw} – mass of FF sample before thermal drying [g];
- m_{d0} – initial mass of a water droplet [g];
- m_{de} – mass of a water droplet after passing through an FF layer [g];
- m_s – fuel load [kg/m^2];
- Δm – parameter characterizing a change in the mass when passing through an FF layer [g];
- R_d – water droplet radius [mm];
- S_f – area of an FF sample cross section [m^2];
- t – time [s];
- T_f – FF temperature [K];
- U_f – instantaneous velocity of water droplets passing through an FF layer [m/s];
- V_d – water droplet volume [μL];
- α_s – fuel packing ratio [-];
- ρ_f – density of FF in a sample [kg/m^3];
- ρ_s – fuel density [kg/m^3];
- γ_f – moisture content of FF [%].

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