Physics of Suppression of Thermal Decomposition of Forest Fuel Using Surface Water Film

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Abstract—The paper presents results of an experimental study of the suppression of thermal decomposition of forest fuel (FF) due to formation of a thin surface water film (3 mm thick). The investigations were carried out with birch leaves, as well as a mixture of birch leaves, pine needles, and twigs of aspen. The experiments involved model bases of fire of the above FFs in the form of cylinders. The cylinders were 20 mm to 60 mm in diameter and 40 mm to 100 mm high. The effect of water on the FFs was monitored via high-speed (up to 10^5 frames per second) video recording and fast (a thermal lag of less than 1 s) thermal transducers. The times of termination of FF thermal decomposition and the minimum (required) volumes of water were determined. The feasibility of complete suppression of the FF thermal decomposition process due to formation of a thin surface water film (10−15 times thicker than the reacted material) was experimentally supported. The foundations of the physical model of a complex of processes that occur owing to the water film effect on the forest fuel heated to a high temperature (well above the point of thermal decomposition) were formulated.

INTRODUCTION

The development of up-to-date fire extinguishing technology with application of aircraft are significantly limited [1−3] for several reasons. Those include scarcity of aircraft available to fire fighters, significant maintenance expenses, fuel costs, a relatively small area covered in a local discharge of extinguishing liquid (as compared with the total combustion area), rapid regrowth of the combustion front, high hazard to pilots' health, etc. As a rule, an aircraft that is to quench a large forest fire takes on a maximum possible amount of extinguishing liquid (in particular, water from a lake or river), transports it into the combustion zone, empties the vessels, and returns to refill them. One such cycle takes half an hour to several hours. The rates of fire spread (especially in a gusty wind) can be as high as tens of meters per minute [1−3]. It is often that when the aircraft returns to the combustion zone, it has to begin the work "from scratch." For this reason, research teams in Australia, Canada, USA, Russia, Spain, and other countries have to develop fire-extinguishing technologies with more efficient use of aircraft [4−6].

The results of theoretical [7, 8] and experimental [9, 10] studies have led to a hypothesis that flows of water droplets distributed in space and time can be applied to extinguishing large fires using aircraft. That would solve a few problems at once: temperature reduction due to the heating of the water (droplet flows), flame energy absorption during evaporation of the liquid, and oxidizer ingress blocking by water vapors in the exothermic reaction zone. The rates of evaporation of water drops of different sizes in the flame zone and on the surface of forest fuels (FFs) were determined theoretically [7, 8] and experimentally [9, 10]. It was shown [7, 9] that the proposed approach can enable effective use of almost the total

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volume of fire-extinguishing liquid for fire suppression. Moreover, the mass of fire-extinguishing liquid can be not hundreds (or even tons) of kilograms, but a few kilograms or tens of kilograms (in case of fire areas of tens of square meters). In particular, the results of theoretical studies [7, 8] have shown that the thermal decomposition of typical FFs can be suppressed due to creation of a sufficiently thin water film (3 mm thick) on the FF surface. The times of thermal decomposition cease, which correspond to the times of suppression of ground forest fires, differ slightly in the cases of creation of such films and continuous flooding of the FF surface. The results of [7, 8] illustrate the promising outlook for using much smaller amounts of water for effective fire extinguishing. However, no experimental data justifying the physical hypotheses of [7, 8] have been published so far. Besides, the development of aerosol fire-fighting technology (e.g., [11−14]) also requires reliable experimental data.

The objective of the present work is an experimental study of the physics of heat and mass transfer processes that occur in the formation of a thin water film on the FF surface and lead to suppression of thermal decomposition of the forest fuel.

EXPERIMENTAL STAND AND RESEARCH METHODS

Figure 1 presents a layout of the stand used. The following recording equipment was applied: Phantom V411 video camera 1 (up to 10^5 frames per second), fast (a minimum sampling rate of 0.1 s) National Instruments module NI 9213 2 for recording the readings of temperature sensors, fast-response chromel−alumel thermal transducers (delay times of 1 s at most) 3, PC 4, analytical balance ViBRA HT 84RCE 5 with a 10^{-5} g resolution, a PIV system [9, 10] with QUANTEL EverGreen 70 laser 8 and IMPERX IGV B2020M cross-correlation camera 11.

The research was conducted with two types of FF sample: (1) birch leaves and (2) a mixture of birch leaves, pine needles, and twigs of aspen. The relative initial humidity of the FFs was as follows: birch leaves, 5−8%; pine needles, 7−10%; aspen twigs, 10−14%. After control of the mass, the FF samples were placed in hollow corrugated aluminum cylinders of height h_f and diameter d_f. The parameter d_f
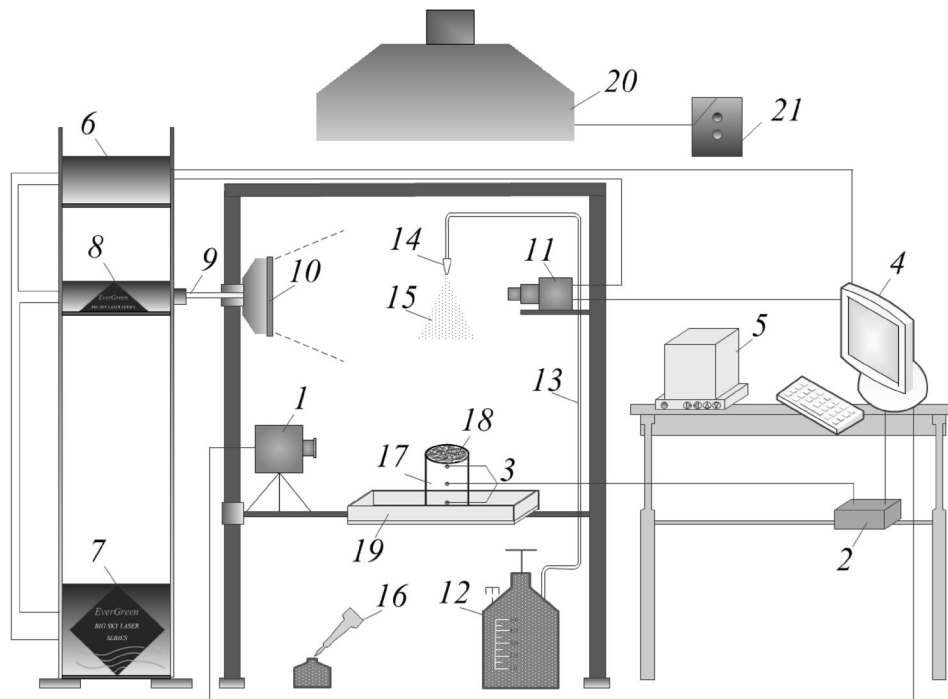

Fig. 1. A layout of the experimental stand: 1—high-speed video camera; 2—analog input module; 3—thermocouples; 4—workstation (PC); 5—laboratory microbalance; 6—signal synchronizer; 7—generator of laser radiation; 8—double-pulse solid-state laser; 9—optical light guide; 10—diffusing screen; 11—cross-correlation video camera; 12—vessel with water; 13—water-supply duct; 14—spray head; 15—water mist (aerosol); 16—electronic single-channel doser; 17—cylinder with FF sample; 18—FF; 19—metal tray; 20—ventilation; 21—ventilation switch.

varied from 20 mm to 60 mm, and h_f ranged from 40 mm to 100 mm. A vertical cutout 3 mm wide was made in each cylinder for visual observation of the FF response. The FF mass was chosen such that the stacking density ρ_f varied from experiment to experiment in a narrow range: birch leaves, $\rho_f = 25-30$ kg/m^3; pine needles, $\rho_f = 30-35$ kg/m^3; aspen twigs, $\rho_f = 100-130$ kg/m^3.

Model bases of fire were ignited using three piezoelectric burners. The time of FF burnout without exposure to water was determined (τ_b), the time from the start of combustion until the readings of all the three thermocouples are less than the thermal decomposition temperature T_f. The average T_f value was considered to be [1] ≈ 370 K.

Water droplets were injected in two modes: continuous supply until a film 3 mm thick arose on the FF surface and flooding of the FF till complete suppression of reaction. The time (τ_e) till the condition $T \leq 370$ K was met was monitored. From 6 to 10 experiments were conducted under identical conditions. The liquid remaining in pan 19 was collected in a beaker, and the liquid volume V_s was determined. The volume of water consumed in the quenching was calculated by the formula $V_e = \mu_w \cdot \tau_e - V_s$, where μ_w is the flow rate ($\approx 3.4 \cdot 10^{-4}$ l/s).

In each experiment, the dimensions (radii) R_d, concentrations γ_d, and velocities U_d of the water droplets were monitored using the PIV system and PIV, SP, and IPI optical methods, similarly to experiments of [9, 10] ($R_d = 0.01-0.1$ mm; $\gamma_d = (1-3) \cdot 10^{-5}$ water liters/gas m^3; $U_d = 0.5-1.5$ m/s). The high-speed camera was recording the process of film rise on the FF surface.

The error in the determination of τ_e, τ_b, and V_e amounted to 0.5 s and $5 \cdot 10^{-4}$ l, respectively. The maximum standard temperature deviations T_f in the interval $0 < \tau < \tau_e$ did not exceed $20-30$ K, i.e., $6-8\%$ or less of the value to measure.

1. RESULTS AND DISCUSSION

Figure 2 presents the experimentally determined times of suppression of FF thermal decomposition with the two above methods of water supply. The times of burnout (τ_b) of the FF samples are also given. Figure 3 illustrates the water amount corresponding to the time τ_e in the experiments.

The processes of the FF pyrolysis stop under exposure to water film, as well as through continuous irrigation with a droplet flow, exhibited close times τ_e (Fig. 2), where $\tau_e \ll \tau_b$. This result can be explained by the combined effect of several physical processes. Two mechanisms of thermal decomposition suppression occurred under a continuous flow of droplets: cooling of the FF to temperature at which the destruction ceased ($T_f \approx 370$ K) and displacement of the oxidant with the water vapor. The droplets penetrated into the reacting FF, thereby cooling it and forcing the decomposition products off its pores. The film that formed on the FF surface prevented air inflow. At the initial stage of the extinguishing, the
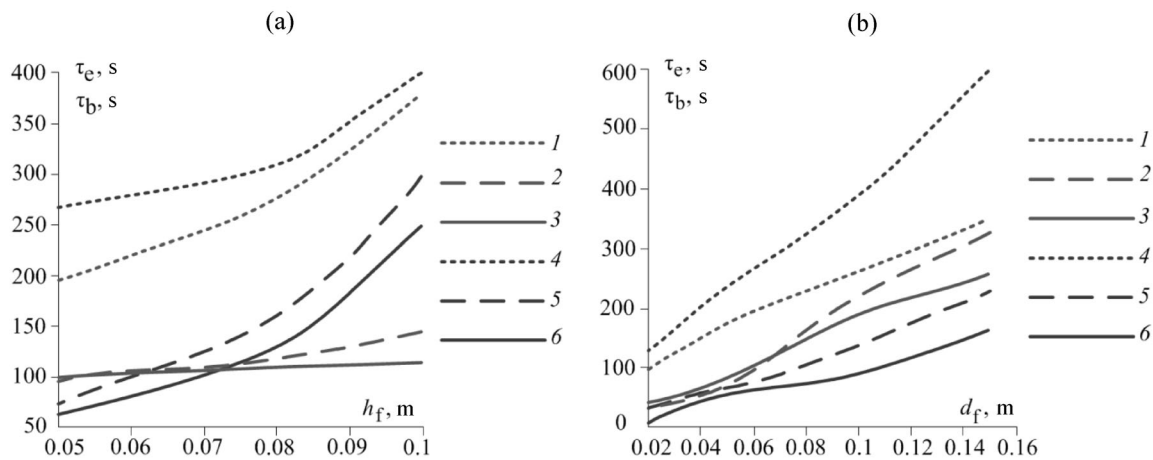

Fig. 2. Durations of processes in question vs. height (a) and diameter (b) of model bases of FF fire: 1—time of burnout of birch leaves (without firefighting); 2—extinction of birch leaves using water film; 3—extinguishment of birch leaves using continuous aerosol flow; 4—times of burnout of FF mixture (without quenching); 5—suppression of combustion of FF mixture using water film; 6—extinction of FF mixture using continuous aerosol flow.

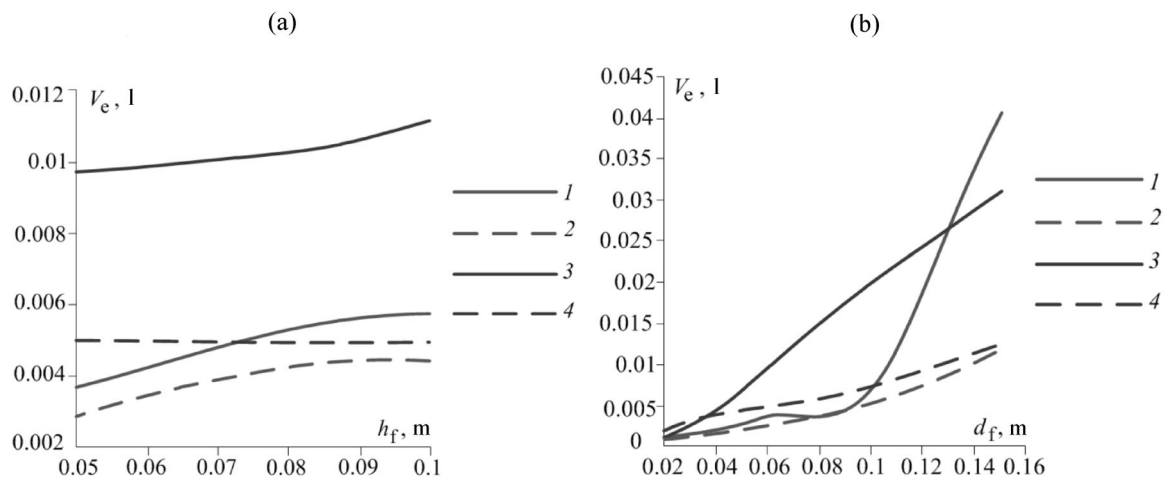(a)   (b)

Fig. 3. Volume of water consumed for suppression of FF thermal decomposition in model bases of fire vs. their height (a) and diameter (b): *1*—quenching of birch leaves using continuous aerosol flow; *2*—extinction of birch leaves using water film; *3*—extinguishment of FF mixture using continuous aerosol flow; *4*—quenching of FF mixture using water film.

water was evaporating intensively, which contributed to the cooling of the FF (thermocouples *3* recorded a decline in the sample temperature by 40–70 K).

Video recording in the experiments revealed that the film was formed on the FF surface as early as in a few tens of seconds since the beginning of water delivery. For example, the formation of a film 3 mm thick on the surface of birch leaves took 25–35 s (with a water consumption $\mu_w \approx 3.4 \cdot 10^{-4}$ l/s and $R_d \approx 30$–100 μm); in the case of FF mixture, the film appeared in 17–22 s. During this time interval, a relatively large volume of water penetrates into the FF pores, most water evaporating in the surface layer. This leads to ingress of water vapor, the thermal conductivity of which is lower than that of the FF, into pores of the reacting FF. The heat flux from the reaction zone to the film goes down. The vaporizing rate declines and the increase in the film thickness does not cause a significant change in τ_e. Still, the τ_e values in continuous flooding of the FF are less as compared with those in the experiments with the film. With an excessive fluid mass, the reason is that its pressure increases (it exceeds the pressure of the vapor and FF decomposition products that are being filtered toward the interface of the media). As a result, larger amounts of water penetrate into the pores and slow down the thermal decomposition.

The experiments demonstrated that the temperature of the thermal decomposition products passing through the water film on the FF surface was significantly lower than that in the zone of their formation. In particular, the temperature in the depth of the reacting layer is as high as 500 K to 600 K, whereas closer to the liquid film it does not exceed 350 K to 370 K. As a result, the low-temperature products of pyrolysis are no longer as dangerous as the fuel in contact with cold air. This outcome evidences that the main mechanism of effective suppression of FF thermal decomposition is the cooling of the FF surface layer. Due to intensive evaporation of water, it is possible to provide a temperature drop below the values corresponding to the onset of thermal decomposition, as well as deeper penetration of water vapor in the heated FF layer. Consequently, there is no need for continuous flooding of pyrolyzed forest fuel with water. The times of thermal decomposition termination are comparable with the times of experiments in which the water supply was limited in time and a thin film of water formed on the FF surface (Fig. 2), whereas the volumes of the fluid discharged differed significantly (Fig. 3).

Experiments with determination of the water film thickness revealed that at the initial stage of formation, the film was rather nonuniform in the thickness direction, containing vapor bubbles. The latter arose as a result of the flow of gaseous products of thermal decomposition, as well as water vapor filtered due to the pressure drop in the porous structure of the decomposing FF heated to high temperatures. With the increasing volume of supplied water, the vapor concentration increased and the temperature in the layer of the reacting FF was going down. As a result, the rate of formation of pyrolysis products was also decreasing, the liquid film thickness equalizing over the surface.

It was found that the volumes V_e (Fig. 3) necessary for thermal decomposition stop differed greatly in the cases of formation of a relatively thin (under 3 mm) film and continuous water supply. It is likely that the water amount sufficient for suppression of the FF pyrolysis can be reduced several times via film formation on the FF surface.

Moreover, the slight impact of the FF sample thickness on the times τ_e and volumes V_e should be noted (Figs. 2 and 3). For example, in the experiments with birch leaves, when the h_f value increased several times, the times τ_e varied within $10-15\%$ only. The insignificant change in the τ_e and V_e values with h_f variation can be explained by the uniform irrigation of the FF surface and the penetration of droplets into the pores of the sample, which leads to close τ_e and V_e values with a slightly varying rate of the FF pyrolysis.

CONCLUSIONS

1. Cooling of FF surface under pyrolysis to temperatures close to the points of thermal decomposition onset (e.g., 370 K) ensures termination of the pyrolysis. Continuous flooding of the FF surface with a liquid would be inappropriate. Efficient cooling of forest fuel is possible due to creation of a thin film of water via pulsed (short) injection.

2. In the case of film formation on the surface of FF under pyrolysis, the water penetrates to a rather small $(5-7$ mm) depth, i.e., only into a thin surface layer. This is due to the intense migration of the thermal decomposition products and formation of water vapor at the bottom boundary of the film. As a result, the main mechanism of suppression of FF thermal decomposition is the cooling of the reacting layer owing to intense endothermic transformations in the surface layer and penetration of vapor into the lower strata of the fuel.

3. The temperature of the gaseous products of thermal decomposition, which pass through the water film, is substantially lower than that in the zone where the products arise. As a result, in contact with the cold oxidant (air) they constitute no danger any more as a fuel.

4. The experiments have allowed us to formulate a physical model of the heat and mass transfer processes in FF thermal decomposition under creation of a thin water film on the fuel surface. At the same time, the satisfactory closeness of the pyrolysis termination times in the cases of birch leaves and a mixture of typical FFs suggests the possibility of extending this result to a large group of forest fuels.

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