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Prediction of Minimum Water Amount to Stop Thermal Decomposition of Forest Fuel

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Abstract—Presented are results of experimental studies of the heat transfer processes in suppression of thermal decomposition of typical forest fuels (FFs) (spruce needles, birch leaves, aspen twigs, or a mixture thereof) due to the effect of aerosol water flow (drop radii: 0.01–0.12 mm; concentration: $3.8 \cdot 10^{-5}$ m^3 drop/m^3 of gas). The experiments have been carried out with FF samples in the form of cylinders of a thickness of 40–100 mm and a diameter of 20–150 mm. The times required to stop the thermal decomposition of FF have been found, as well as amounts of water necessary to lower in a given time the temperature in a layer of material to the point of decomposition beginning. A dimensionless complex has been derived for prediction of water spraying parameters (amount and time of supply) that ensure sustainable termination of FF decomposition within a specified time interval.

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INTRODUCTION

One of the main objectives in the creation of modern fire extinguishing systems is, as a rule, optimization of the flow rate [1–3]. However, no mathematical expressions that give a fully reliable prediction of optimum operating parameters (drop size, mass flow rate, operation time, etc.) of sputtering systems have been derived yet. As a result, quite often the process of fire extinguishing takes more water than necessary for effective suppression of the combustion. The negative consequences of the use of excessive ("superfluous") liquid, e.g., water, in some cases even exceed the effects of the fire itself [1–3].

In recent years, experimental and theoretical studies [4–6] led to conclusions about the possibility of significant minimization of water consumption in fire extinguishing. It has been shown [4–6] that rational time and spatial distribution of water supply to the combustion zone can ensure complete cessation of fire through application of several tens or hundreds of liters instead of the traditionally spent tons of water on areas of up to 50 m^2. To develop the concepts in [4–6], it would be reasonable to derive a dimensionless complex that enables prediction of required parameters of water supply to the combustion zone. To select the basic dimensional variables that define the process to study in accordance with the similarity theory [7], it is necessary to conduct experiments with combustion areas with samples of different types of FF.

The objective of the work is to derive from experimental results a dimensionless complex to predict water sputtering parameters that correspond to establishment of conditions for suppression of thermal decomposition of FFs in a predetermined time period.

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METHODOLOGY OF EXPERIMENTS

In this work, the most widespread FFs (in accordance with statistical data [8]) were used: samples of birch leaves, spruce needles, aspen twigs, and mixtures thereof (birch leaves: 25%, spruce needles: 15%, aspen twigs: 60%). The forest fuel was dried beforehand for 3–5 days at a temperature of about 300 K. The relative humidity of the material, which was determined from the mass before and after the drying, was as follows: birch leaves, 5–8%; spruce needles, 7–10%; aspen twigs, 10–14%. The model combustion areas were created using hollow corrugated-aluminum cylinders with a height h_f and a diameter d_f. In these experiments, the d_f parameter varied in the range of 20–150 mm, and the h_f one was 40 mm to 100 mm. As a result, the volume of FF sample $V_\mathrm{f} = 0.5\text{–}15 \cdot 10^{-5}$ m^3. The maximum value $V_\mathrm{fmax} = 15 \cdot 10^{-5}$ m^3 was taken as a scale parameter in the processing of the results of the experiments. The initial FF mass was chosen such that the FF density ρ_f varied little from experiment to experiment: birch leaves, $\rho_\mathrm{f} = 25\text{–}30$ kg/m^3; spruce needles, $\rho_\mathrm{f} = 30\text{–}35$ kg/m^3; aspen twigs, $\rho_\mathrm{f} = 100\text{–}130$ kg/m^3. The choice of the material density depended on FF burning features: a low-density FF would rapidly burn out, whereas a high-density one would smolder.

A scheme of the experimental stand is shown in Fig. 1. Needle thermocouples (CA, temperature range: 223–1473 K, error ±3 K; time lag no more than 1 s) to monitor the temperature in the zone of thermal decomposition of FF were placed at three points on the vertical symmetry axis (h_f) of the sample. Three piezoelectric gas burners simultaneously set the sample on fire, uniformly over the open FF surface. The thermal decomposition was believed to occur at an FF temperature of above 370 K on one of the three thermocouples, which were located at different heights in the thickness of the FF. The moment when the temperature in the reaction zone dropped below this value was regarded as the end of the thermal decomposition. The cylinders had a vertical cutout 3 mm wide, which was made for visual observation.

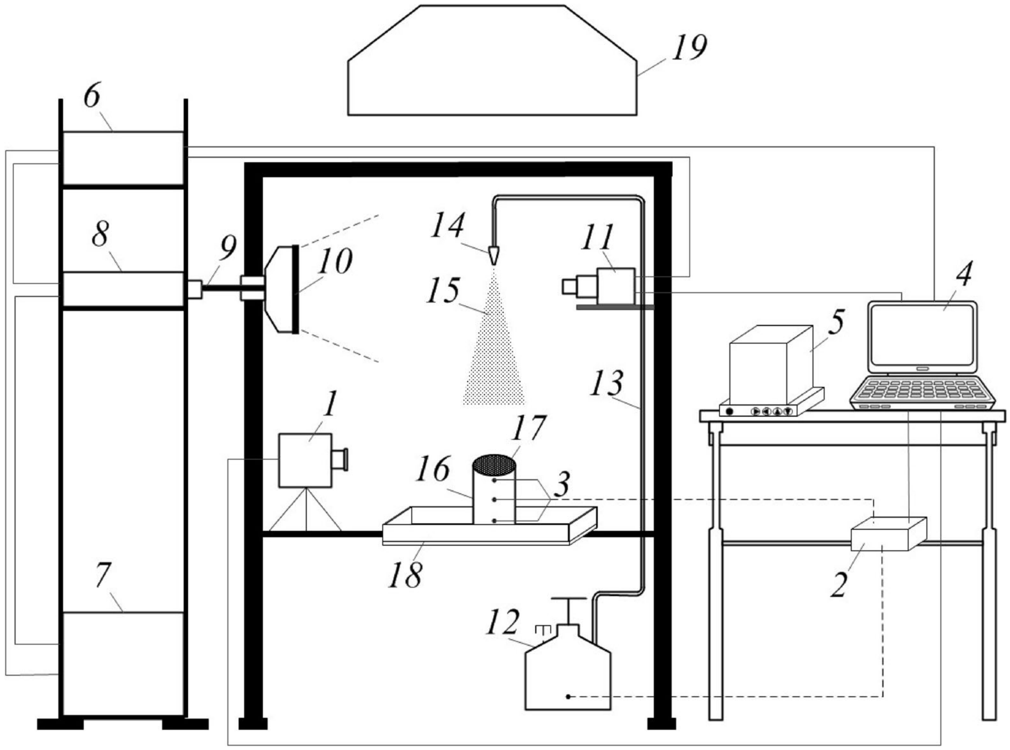

Fig. 1. Diagram of experiments: *1*—high-speed video camera; *2*—high-speed analog-input module; *3*—thermocouples; *4*—workstation (PC); *5*—laboratory microbalance; *6*—signal synchronizer; *7*—laser radiation generator; *8*—double solid pulsed laser; *9*—optical waveguide; *10*—diffusing screen; *11*—cross-correlation video camera; *12*—tank with water; *13*—water supply passage; *14*—spray nozzle; *15*—water mist; *16*—cylinder with FF sample; *17*—FF; *18*—metal tray; *19*—exhaust ventilation.

The process of extinguishing of FF combustion was implemented through spraying water above the FF surface (drop radii $R_\mathrm{d} = 0.01–0.12$ mm; initial motion speed $U_\mathrm{d} \approx 2$ m/s; gas concentration $\gamma_\mathrm{d} = 3.8 \cdot 10^{-5}$ m^3 drop/m^3 of gas; consumption $\mu_\mathrm{d} = 3.5 \cdot 10^{-4}$ m^3/s). The spraying parameters U_d, γ_d, R_d, and μ_d were monitored using the panoramic techniques SP and PTV, as in the experiments in [4–6]. The times of decomposition suppression t_e were recorded once the temperature in the reaction zone lowered to 370 K, by the readings of all the three thermocouples. The times of complete burnout of the FFs without water supply (t_b) were also recorded.

The injection of the water spray formed a film up to 5 mm thick on the FF surface, which was recorded by a high-speed video camera (up to 100,000 frames per second). The times t_b and t_e were checked through synchronization of the three thermocouples and the video camera. For satisfactory reproducibility of the experimental results, six to ten experiments were performed under identical conditions. When the results of the determination of t_b and t_e deviated from the average values (in one series under identical conditions) by more than 5%, the data of these measurements were excluded from consideration. The fraction of such experiments from the total number did not exceed 3%.

RESULTS AND DISCUSSION

Figure 2 shows the times of termination of thermal decomposition (t_e) (complete suppression of the process due to the water sprinkling) and complete burnout (t_b) of FF without exposure to water. The birch leaves had the smallest times t_b, e.g., $t_\mathrm{b} = 90$ s at $d_\mathrm{f} \approx 20$ mm and $h_\mathrm{f} \approx 40$ mm. In the case of spruce needles under identical conditions, the same times t_b were 105 s. The largest times t_b, 350 s, were recorded in the case of twigs. It should be noted that the t_e values were much smaller than the t_b ones in all the experiments (Fig. 2). In particular, the FF mixture yielded the minimum times t_e (less than 1 min), which is due to the FF structure and the features of water penetration into the pores of the FF. Besides that, the water volume V_e spent on the termination of thermal decomposition of FF was found to be relatively moderate for different sample volumes V_f. This result characterizes the efficiency of the fire extinguishing process.

The experiments simultaneously used two mechanisms of suppression of the FF reaction: cooling the material to the point of termination of thermal decomposition ($T_\mathrm{f} \approx 370$ K) and displacing the oxidant from the combustion zone. Drops of water penetrated deep into the FF, cooling it from inside and forcing (due to intense vaporization) the oxygen out of the wall region. The water film that had formed on the surface of the FF prevented its upper layers from igniting and hindered the air inflow. Furthermore, at the initial stage of the experiment, the flame combustion of the FF occurred simultaneously with intense evaporation of water drops, which contributed to further cooling of the combustible material and displacement of the oxidant out of the wall region together with the leaving water vapor (the thermocouples read out a temperature decrease of 50–70 K in the upper layer of the FF under vigorous evaporation of the drops). The supply of water mist minimized the excess of the liquid (almost all the water evaporated during the extinguishing, and there remained a volume of less than 5–7% of V_e on the tray (Fig. 1)).

Analysis of the effect of the sample thickness and diameter on the times t_e indicated a common character of the curves $t_\mathrm{e} = f(d_\mathrm{f})$ and $t_\mathrm{e} = f(h_\mathrm{f})$ but essentially different dynamics of the time of decomposition termination. With h_f growing even by 50%, the times t_e changed within 20%, while even a 15–20% increment in d_f led to a 30–40% increase in the times t_e. The high importance of uniform sprinkling of the FF surface should be noted.

When summarizing the experimental results, it would be reasonable to estimate the water volume expended in suppressing the thermal decomposition. To this end, in the first approximation, one can compare the energy for evaporation of the water and that accumulated in the thermal decomposition of the FF in the layer of the material.

Under an assumption of uniform heating of the FF and all the energy of the phase transition spent on the evaporation, the energy balance in the area of thermal decomposition in the first approximation can be written as follows:

$$C_\mathrm{f}\rho_\mathrm{f} dT/dt = -W_\mathrm{e}Q_\mathrm{e}/h_\mathrm{f}.$$

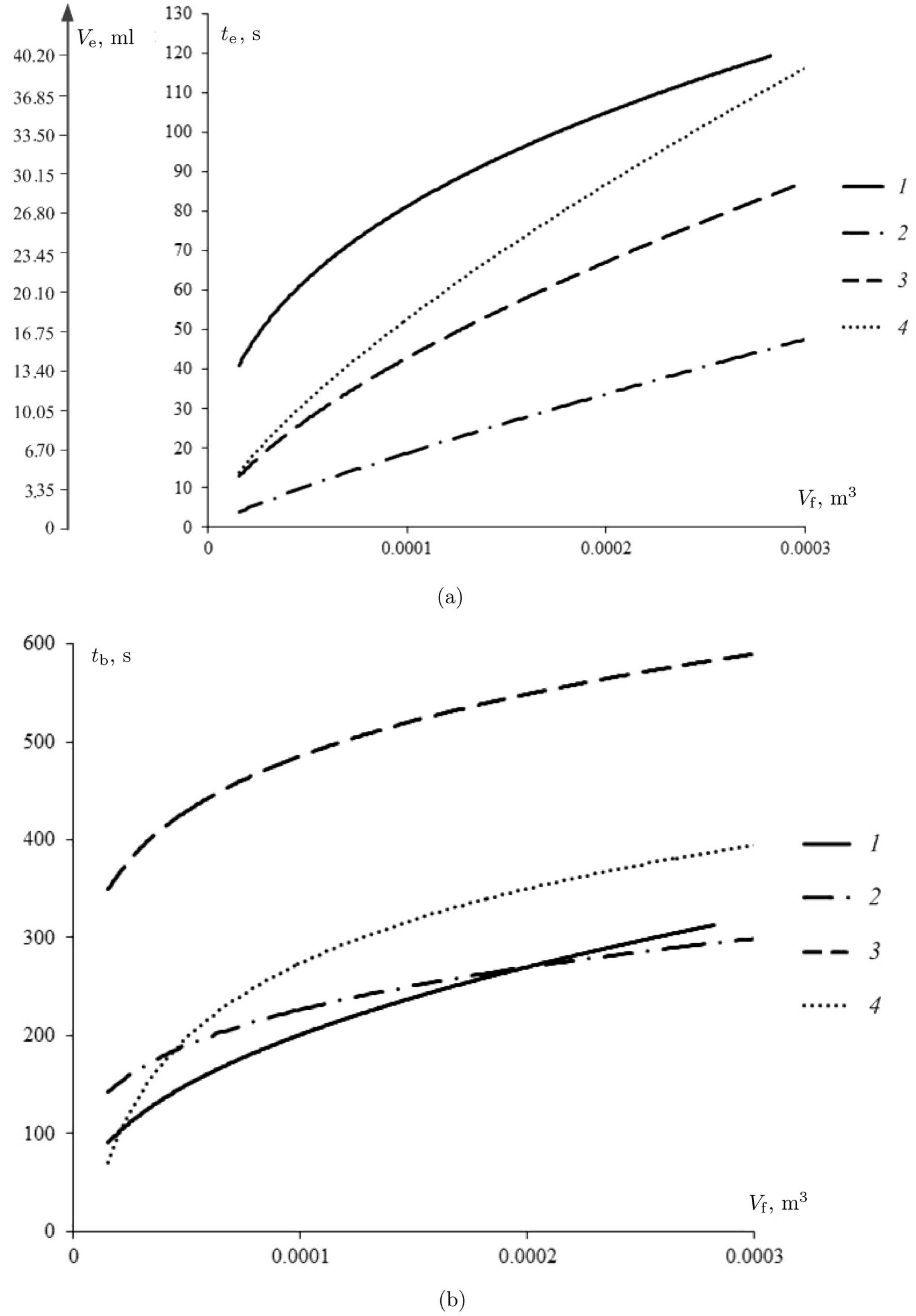

Fig. 2. (a) Times of complete suppression of thermal decomposition of FF versus FF volume and water consumption; (b) times of complete burnout of FF without water supply (*1*—leaves, *2*—spruce needles, *3*—aspen twigs, *4*—mixture of FFs).

After transformations we obtain

$$\int_{T_{\mathrm{it}}}^{T_{\mathrm{m}}} dT + \int_{T_{\mathrm{m}}}^{T_{\mathrm{it}}} dT = -W_{\mathrm{e}}Q_{\mathrm{e}}S_{\mathrm{f}}t/(C_{\mathrm{f}}\rho_{\mathrm{f}}V_{\mathrm{f}}).$$

As a result of integration we have

$$T - T_{\mathrm{m}} = -W_{\mathrm{e}}Q_{\mathrm{e}}S_{\mathrm{f}}t/(C_{\mathrm{f}}\rho_{\mathrm{f}}V_{\mathrm{f}}).$$

After reduction to a dimensionless form, dividing the above expression by the temperature difference $T_{\mathrm{m}} - T_{\mathrm{it}}$, we obtain

$$(T_{\mathrm{m}} - T)/(T_{\mathrm{m}} - T_{\mathrm{it}}) = W_{\mathrm{e}}Q_{\mathrm{e}}S_{\mathrm{f}}t/(C_{\mathrm{f}}\rho_{\mathrm{f}}V_{\mathrm{f}}(T_{\mathrm{m}} - T_{\mathrm{it}})).$$

The product $W_{\mathrm{e}}S_{\mathrm{f}}t$ is the mass of evaporated water m_{w}; the latter value can be determined from the product $\mu_{\mathrm{d}}\rho_{\mathrm{w}}t$. Taking $m_{\mathrm{w}} = \mu_{\mathrm{d}}\rho_{\mathrm{w}}t$ into account, we obtain

$$(T_{\mathrm{m}} - T)/(T_{\mathrm{m}} - T_{\mathrm{it}}) = Q_{\mathrm{e}}\mu_{\mathrm{d}}\rho_{\mathrm{w}}t/(C_{\mathrm{f}}\rho_{\mathrm{f}}V_{\mathrm{f}}(T_{\mathrm{m}} - T_{\mathrm{it}})). \tag{1}$$

The left-hand side of (1) represents the dimensionless temperature, which characterizes the thermal condition of the FF in the reaction (from the beginning of the decomposition until achievement of T_{m} and then decrease to values less than T_{it}). The right-hand side shows the ratio of the energies spent on the phase transition and accumulated in the reacting FF. To predict the required water amount and

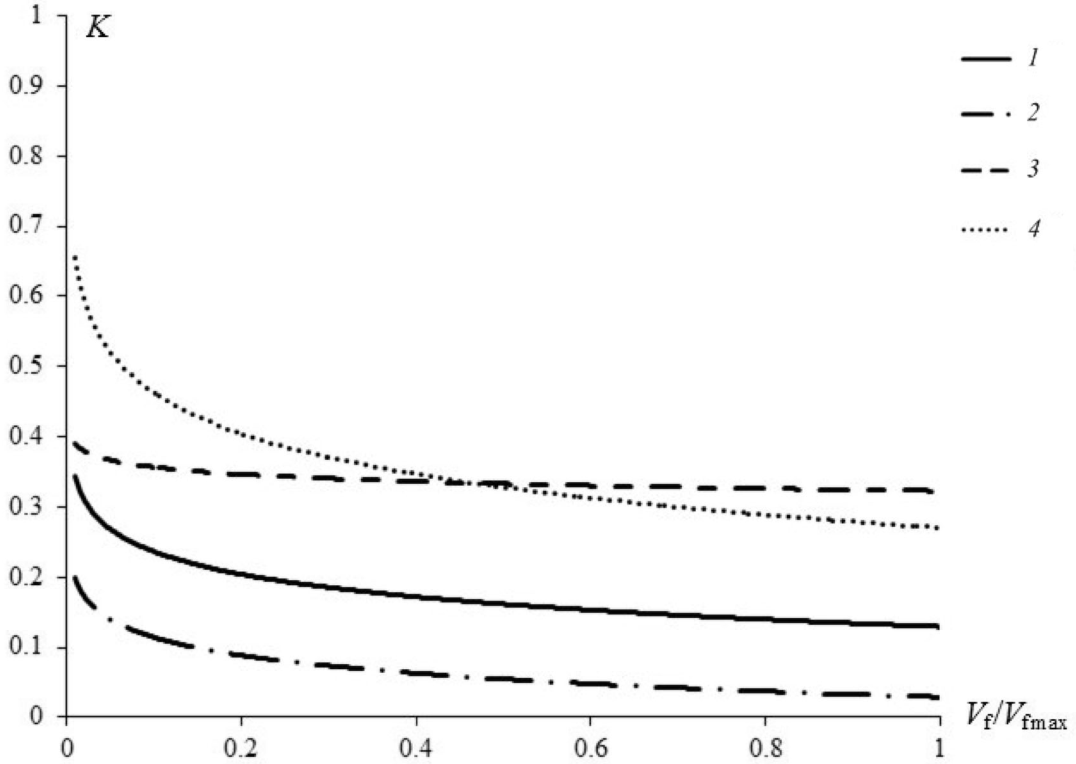

Fig. 3. Dimensionless complex K versus sample volume: *1*—birch leaves, *2*—spruce needles, *3*—aspen twigs, *4*—mixture of FFs.

time for suppression of the reaction, one can, in accordance with the basic provisions of the theory of similarity [7], use the following dimensionless complex:

$$K = Q_\mathrm{e}\mu_\mathrm{d}\rho_\mathrm{w}t/(C_\mathrm{f}\rho_\mathrm{f}V_\mathrm{f}(T_\mathrm{m} - T_\mathrm{it})).$$

Figure 3 shows the dimensionless criterion complex K versus the relative volume of the FF. The values of the thermal characteristics of the FF were taken in accordance with [8]. Analysis of the results in [8] demonstrates that the thermal characteristics of the FF can vary in the range of 10–15%, which cannot significantly affect the value of the complex K.

Note the close character of the dependences in Fig. 3 for different FF types, which reflects the general physical laws of termination of the decomposition process. It can be concluded that the K values vary for each FF type in a very narrow range (e.g., 0.17 to 0.33), especially so with growth of V_f. Therefore, the complex K can be used for prediction of water spray parameters (flow rate, supply time, and areas of evaporation surface) required for given times of fire extinguishing. This conclusion has been justified for large FF sample volumes V_f, which correspond to actual forest fires.

CONCLUSIONS

The results of the experiments on the suppression of FF combustion using water drops have made it possible to link the basic parameters of the process under study (decomposition temperature, FF material properties, volume of this material layer, water flow, and duration of spraying) and formulate a dimensionless complex that can be used in determination of water spraying parameters (in particular, in specialized aerosol supply [9]) required for efficient termination of thermal decomposition of typical forest fuels.

NOTATIONS

C_f—FF heat capacity, J/(kg·K)
d_f—FF sample diameter, m
h_f—FF sample thickness, m
K—dimensionless parameter
m_w—mass of evaporated water, kg
R_d—initial drop radius, mm
Q_e—thermal effect of vaporization, MJ/kg
S_f—FF surface area (evaporation surface area), m^2
t—time, s
t_b—time of complete burnout of FF, s
t_e—time of completion of thermal decomposition, s
T—sample volume average temperature, K
T_m—maximum temperature (combustion temperature) of FF, K
T_it—temperature of thermal decomposition beginning, which was assumed to be 370 K in the analysis of the experiments, in accordance with [7]
U_d—initial velocity of drops, mm
V_e—volume of water spent on suppression of combustion of FF, m^3
V_f—FF sample volume, m^3
V_fmax—FF maximum sample volume, m^3
W_e—evaporation rate, $\mathrm{kg/(m^2s)}$
γ_d—drop concentration in aerosol flow, m^3 drop/m^3 of gas
μ_d—flow m^3/s
ρ_f—FF density, $\mathrm{kg/m^3}$
ρ_w—water density, $\mathrm{kg/m^3}$

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