

CHARACTERISTICS OF MOISTURE RELEASE FROM LAYERS OF FOREST FUELS WITH TYPICAL FIRE EXTINGUISHING AGENTS

by

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Typical fire extinguishing agents were considered: water, bischofite solutions, bentonite slurries, and foaming agent emulsions (with a mass fraction of 5% and 10%). The heating temperature range of 150–400 °C was chosen to correspond to the conditions of rapid thermal decomposition of forest fuels. The experimental research findings suggest that the rates of moisture release depend exponentially on the heating temperature. It was established that the rates of moisture release in the above temperature range may differ significantly for the forest fuels and fire extinguishing agents under study. Conditions were identified when the general approximation equations, presented in this paper, can be used to predict the vaporization characteristics of firefighting liquids.

Key words: forest fuel, wetting, heating, evaporation, rates of moisture release, firefighting additives

Introduction

A group of methods, approaches and technologies utilizing liquid spraying systems were developed to contain and suppress the thermal decomposition and flame combustion of woodland [1-3]. These systems facilitate the containment of flame combustion and thermal decomposition of materials [4-7]: high heat capacity of water and energy-consuming endothermic phase transition decrease the temperature in the combustion zone and in the layers of pyrolyzing material, thermal decomposition products are displaced by water vapors, and liquid droplets and vapors block the heated oxidizer access to the pyrolysis and combustion zone.

Due to their availability, water-based compositions (solutions, slurries and emulsions) are widely used in forest fuel fire containment and suppression [6]. They do not require any special purification. Moreover, the vaporization heat and heat capacity of water are high enough for the efficient accumulation of combustion energy.

The type of components, their properties and concentrations in aqueous solutions, emulsions and slurries should be chosen with due consideration of typical conditions of their application in real-life firefighting technologies. Surfactants have considerable potential as an additive to fire-extinguishing compositions. Therefore, it seems rational to obtain experimental data about the effect of surfactant concentration on the interaction of forest fuels with liquid droplets with different component compositions [8]. Solid particles may play a significant part, too. In particular, Kuznetsov *et al.* [5] carried out experiments to investigate the patterns of fire

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suppression using graphite slurries (1 wt.%, 2 wt.%). It was established [5] that solid particles triggered the accumulation of flame energy in the thin near-surface layer of droplets and facilitated water boiling, subsequent breakup, and formation of a cloud of fine liquid fragments. This occurred because their optical properties differed significantly from those of water. The surface area of the fire extinguishing liquid increased more than tenfold. This enhanced the convective heat exchange of the liquid with high temperature gases in the flame combustion zone and endothermic phase transformations. Such conditions contributed to a rather fast temperature reduction of the burning material surface and in the flame combustion zone due to high heat capacity and vaporization heat of water. Bentonite-based fire extinguishing agents traditionally feature high integral efficiency indicators in fighting fires and prevention of fire outbreaks [9-11].

The convective and radiant heat supply to the forest fuel surface are the most typical mechanisms [12-15]. The following conditions should be provided when using control lines: long-lasting retention of moisture in the layers of the material ahead of pyrolysis and flame combustion fronts (while the material is burning out), on the one hand, and energy absorption as a result of rapid vaporization, on the other hand. This can ensure that even a vast combustion source is contained. It is, therefore, important to reliably predict the rates of moisture release from the forest fuel samples (moisture released as vapors contributes to a rapid reduction in the combustion zone temperature). It is tricky to reproduce the convective heating with real gas velocities (several meters per second) relative to the material sample surface, using experimental set-ups. Thus, it is reasonable to conduct experiments with radiant heating at the first stage. Moreover, the radiant heat flux to the forest fuel surface in front of the control line is usually dominant [4-6]. The temperature range should be chosen using the mean values recorded in the thermal decomposition and combustion front of forest fuels ahead of control lines. It was shown [4-6] that the mean values of these temperatures in the samples of pine needles, leaves and a mixture of materials range from 150-400 °C.

Considering aforementioned, the main objective of the experimental research was to determine the instantaneous (at each particular point of time) and mean (over the whole evaporation period) mass rates of moisture release (at a first approximation, evaporation of liquid from the free surface) from typical forest fuels, as illustrated by water without additives, emulsions with aqueous film-forming foam (AFFF), bischofite solutions and bentonite slurries. The purpose of this study is to establish approximation equations, using experimental findings, for the rates of moisture release from the forest fuel samples under radiant heating conditions typical of forest fires *vs.* a group of decisive factors: heating temperature, initial volume of liquid, component composition, and properties of forest material. These mathematical equations could be used in the real practice of firefighting when developing forest fire containment technologies.

Experimental set-ups and methods

After generalizing the established patterns [8-11], the following typical fire extinguishing liquids were selected: water without additives, emulsion with a foaming agent AFFF (with a mass fraction of 5% and 10%), bischofite solutions with a mass fraction of 5% and 10% (bischofite is a hydrous magnesium chloride mineral, widely used to suppress forest and grassland fires and protect wooden structures from fires), and bentonite slurries with a mass fraction of 5% and 10% (bentonite is an absorbent aluminum phyllosilicate clay, creating a protective coke layer on the forest fuel surface and keeping out air). The object of the research was typical forest litter (pine needles, leaves, and a mixture of forest fuels – leaves, twigs and needles), forming the forest floor and being more fire-hazardous than live plants (it is the forest floor that contains an abundance of combustible components). The mass, density, and thickness

of the forest fuel layer were taken into account. These characteristics corresponded to the real conditions of forest litter (layer height about 40 mm, forest fuel density depends on the material and is between 5 kg/m³ and 15 kg/m³). The temperature in the chamber was a variable parameter ($T_{\text{muf}} = 150\text{--}400\text{ }^{\circ}\text{C}$). The temperature increased in increments of 50 $^{\circ}\text{C}$. The following parameters were recorded: time of liquid evaporation and mass of the evaporated liquid. The errors of determining the rate and time of moisture release did not exceed 13% and 5%, respectively. Like in any experiment, there were systematic and random errors. Systematic errors characterize the equipment used, whereas random errors are related to the conditions of measurements in a series. Figure 1 shows the main equipment used and the material samples after liquid spraying.



Figure 1. Main components and equipment used in the experiments: 1 – wet forest fuel sample, 2 – aluminum cuvette, and 3 – muffle furnace

The experimental technique included the procedures:

- forest fuel sample was dried for three to five days at a temperature of about 300 K,
- the cuvette – 2 (length $L \approx 100$ mm, width $N \approx 95$ mm, height $H \approx 40$ mm) was filled with the forest fuel – 1,
- the necessary temperature was set in the muffle furnace – 3 (we used an EKPS-10 electric muffle furnace: operating temperature range 50–1100 $^{\circ}\text{C}$, temperature setting accuracy $\pm 1\text{ }^{\circ}\text{C}$, free volume of the operating chamber – 10 L); the temperature inside the furnace T_{muf} was varied between 150 $^{\circ}\text{C}$ and 400 $^{\circ}\text{C}$ in the experiments,
- the forest fuel sample mass, m_f , was recorded using an electronic analytical balance, it was about 20 g; the aluminum cuvette mass: $m_{\text{sub}} \approx 6$ g, the sample bulk density: $\rho_f \approx 13.5\text{ kg/m}^3$ (corresponds to the mean range of the real forest floor density),
- a liquid composition with a regulated component concentration was injected into the forest fuel sample – 1; for that we used a spraying nozzle, generating water aerosol with the radius of droplets $R_d = 0.01\text{--}0.12$ mm,
- using the balance (ViBRA HT 84RCE weighing system (the minimum and maximum weight is 0.01 g and 80 g with an accuracy of 0.0001 g), we determined the mass of the forest fuel sample with water (or aqueous solution); the mass of the liquid fire extinguishing solution in the forest fuel layer m_s was about 7 g,
- the cuvette – 2 with the forest fuel sample – 1 was placed into the muffle furnace – 3, and
- the mass of the forest fuel sample with a fire extinguishing agent was recorded with a time increment, Δt , of 15–60 seconds; the higher the heating temperature, the smaller Δt .

The material was not ignited in the muffle furnace during heating. The threshold ignition temperature of all the plant materials under study is 500 $^{\circ}\text{C}$. The average combustion temperature of forest fuels is between 500–900 $^{\circ}\text{C}$. Measurements continued until the liquid completely evaporated from the forest fuel layer. Five measurements were performed for identical experimental conditions (temperature, type of forest fuel, fire extinguishing agent). The results were then averaged. The confidence interval at the 0.95 confidence level was on average 10–15% of the said values.

Using the experimental findings, we calculated the instantaneous, W_{ei} , and average, W_{ea} , mass rates of evaporation of water without additives, compositions with a foaming agent, bischofite and bentonite from the forest fuel layer surface. The following formulas were used:

$$W_{ei} = \Delta m / (S_f \Delta t) \text{ kg/m}^2\text{s}, W_{ea} = m / (S_f t_e) \text{ kg/m}^2\text{s}$$

where Δm [kg] is the decrease in the mass of liquid in the forest fuel sample within Δt , t_e [s] – the time of the whole liquid mass, m , evaporation from the forest fuel sample, $S_f = NH$ [m²] – the free surface area of the forest fuel sample. At a first approximation, it was interesting to evaluate the rates of moisture release from the free surface of the sample. In the future, it makes sense to study the structure of the material sample and calculate the rate of moisture release with due consideration of the surface area of individual elements of the porous structure of the forest fuel sample.

Results and discussion

Figure 2 presents typical rates of moisture release (vaporization rates) for water without additives at various ambient temperatures, calculated using experimental findings. The same parameters were determined for all the compositions under study: solutions, emulsions, and slurries. Figure 3, in particular, presents data for different compositions at a muffle furnace temperature of about 300 °C. The research findings showed significantly non-linear dependence

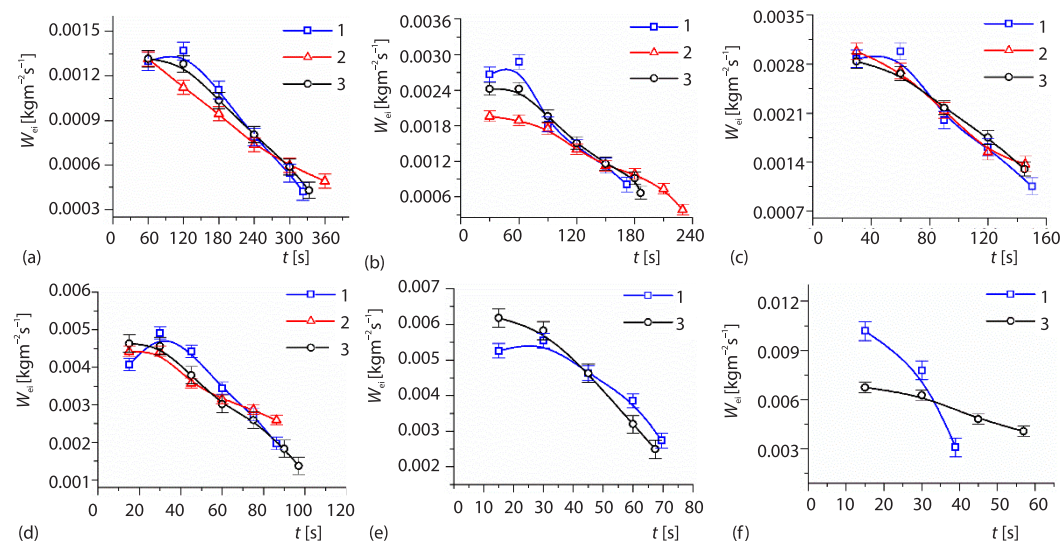


Figure 2. Instantaneous mass rates of evaporation, W_{ei} , of water without additives from the forest fuel surface ($\rho_f \approx 31 \text{ kg/m}^3$) vs. time; (a) $T_{muf} \approx 150 \text{ }^\circ\text{C}$, (b) $T_{muf} \approx 200 \text{ }^\circ\text{C}$, (c) $T_{muf} \approx 250 \text{ }^\circ\text{C}$, (d) $T_{muf} \approx 300 \text{ }^\circ\text{C}$, (e) $T_{muf} \approx 350 \text{ }^\circ\text{C}$, and (f) $T_{muf} \approx 400 \text{ }^\circ\text{C}$; $W_{ei} = at^3 + bt^2 + ct + d$: 1 – needles, 2 – leaves, and 3 – FF mixture; (a) 1 – $a = 1 \cdot 10^{-10}$, $b = -8 \cdot 10^{-8}$, $c = 1 \cdot 10^{-5}$, $d = 8 \cdot 10^{-4}$; 2 – $a = 2 \cdot 10^{-11}$, $b = -7 \cdot 10^{-9}$, $c = 2 \cdot 10^{-6}$, $d = 15 \cdot 10^{-4}$; 3 – $a = 5 \cdot 10^{-11}$, $b = -3 \cdot 10^{-8}$, $c = 4 \cdot 10^{-6}$, $d = 12 \cdot 10^{-4}$; (b) 1 – $a = 2 \cdot 10^{-9}$, $b = -8 \cdot 10^{-8}$, $c = 1 \cdot 10^{-5}$, $d = 8 \cdot 10^{-4}$; 2 – $a = 2 \cdot 10^{-11}$, $b = -7 \cdot 10^{-9}$, $c = -2 \cdot 10^{-6}$, $d = 15 \cdot 10^{-4}$; 3 – $a = 5 \cdot 10^{-11}$, $b = -3 \cdot 10^{-8}$, $c = 4 \cdot 10^{-6}$, $d = 12 \cdot 10^{-4}$; (c) 1 – $a = 3 \cdot 10^{-9}$, $b = -8 \cdot 10^{-7}$, $c = 5 \cdot 10^{-5}$, $d = 20 \cdot 10^{-4}$; 2 – $a = 2 \cdot 10^{-9}$, $b = -6 \cdot 10^{-7}$, $c = 3 \cdot 10^{-5}$, $d = 26 \cdot 10^{-4}$; 3 – $a = 7 \cdot 10^{-10}$, $b = -3 \cdot 10^{-7}$, $c = 1 \cdot 10^{-5}$, $d = 27 \cdot 10^{-4}$; (d) 1 – $a = 1 \cdot 10^{-10}$, $b = -8 \cdot 10^{-8}$, $c = 1 \cdot 10^{-5}$, $d = 8 \cdot 10^{-4}$; 2 – $a = 2 \cdot 10^{-11}$, $b = -7 \cdot 10^{-9}$, $c = 2 \cdot 10^{-6}$, $d = 15 \cdot 10^{-4}$; 3 – $a = 5 \cdot 10^{-11}$, $b = -3 \cdot 10^{-8}$, $c = 4 \cdot 10^{-6}$, $d = 12 \cdot 10^{-4}$; (e) 1 – $a = 1 \cdot 10^{-8}$, $b = -3 \cdot 10^{-6}$, $c = 1 \cdot 10^{-4}$, $d = 42 \cdot 10^{-4}$; 3 – $a = 2 \cdot 10^{-8}$, $b = -4 \cdot 10^{-6}$, $c = 1 \cdot 10^{-4}$, $d = 53 \cdot 10^{-4}$; and (f) 1 – $a = 0$, $b = -2 \cdot 10^{-5}$, $c = 5 \cdot 10^{-4}$, $d = 57 \cdot 10^{-4}$; 3 – $a = 9 \cdot 10^{-18}$, $b = -1 \cdot 10^{-5}$, $c = 3 \cdot 10^{-4}$, $d = 45 \cdot 10^{-4}$

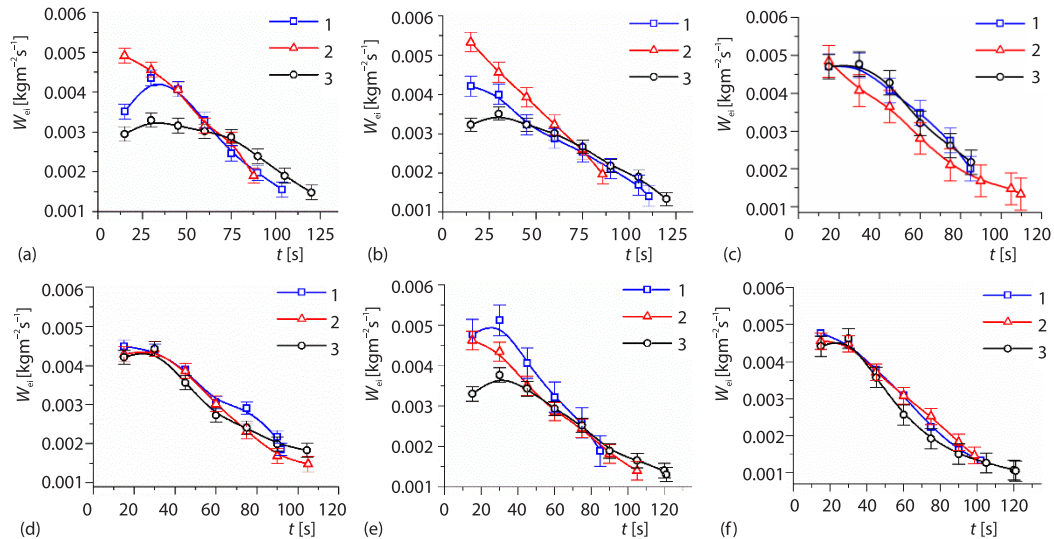


Figure 3. Instantaneous rates of moisture release from forest fuel samples at $T_{\text{mur}} \approx 300^\circ\text{C}$ for various fire extinguishing agents; (a) foaming agent emulsion (mass fraction of 5%), (b) foaming agent emulsion (mass fraction of 10%), (c) bischofite solution (mass fraction of 5%), (d) bischofite solution (mass fraction of 10%), (e) bentonite slurry (mass fraction of 5%), and (f) bentonite slurry (mass fraction of 10%); $W_e = at^3 + bt^2 + ct + d$; 1 – needles, 2 – leaves, and 3 – FF mixture; (a) 1 – $a = 2 \cdot 10^{-8}$, $b = -3 \cdot 10^{-6}$, $c = 2 \cdot 10^{-4}$, $d = 17 \cdot 10^{-4}$; 2 – $a = 9 \cdot 10^{-10}$, $b = -4 \cdot 10^{-7}$, $c = -1 \cdot 10^{-5}$, $d = 52 \cdot 10^{-4}$; 3 – $a = 2 \cdot 10^{-9}$, $b = -6 \cdot 10^{-7}$, $c = 4 \cdot 10^{-5}$, $d = 25 \cdot 10^{-4}$; (b) 1 – $a = -6 \cdot 10^{-10}$, $b = 1 \cdot 10^{-7}$, $c = -4 \cdot 10^{-5}$, $d = 48 \cdot 10^{-4}$; 2 – $a = -4 \cdot 10^{-9}$, $b = -6 \cdot 10^{-7}$, $c = -7 \cdot 10^{-5}$, $d = 63 \cdot 10^{-4}$; 3 – $a = 2 \cdot 10^{-9}$, $b = -7 \cdot 10^{-7}$, $c = 3 \cdot 10^{-5}$, $d = 29 \cdot 10^{-4}$; (c) 1 – $a = 4 \cdot 10^{-9}$, $b = -1 \cdot 10^{-6}$, $c = 3 \cdot 10^{-5}$, $d = 45 \cdot 10^{-4}$; 3 – $a = 2 \cdot 10^{-8}$, $b = -3 \cdot 10^{-6}$, $c = 1 \cdot 10^{-4}$, $d = 36 \cdot 10^{-4}$; (d) 1 – $a = 3 \cdot 10^{-9}$, $b = -6 \cdot 10^{-7}$, $c = 7 \cdot 10^{-6}$, $d = 46 \cdot 10^{-8}$; 2 – $a = 1 \cdot 10^{-8}$, $b = -2 \cdot 10^{-6}$, $c = 9 \cdot 10^{-5}$, $d = 35 \cdot 10^{-4}$; 3 – $a = 1 \cdot 10^{-8}$, $b = -2 \cdot 10^{-6}$, $c = 5 \cdot 10^{-5}$, $d = 39 \cdot 10^{-4}$; (e) 1 – $a = 2 \cdot 10^{-8}$, $b = -3 \cdot 10^{-6}$, $c = 1 \cdot 10^{-4}$, $d = 37 \cdot 10^{-4}$; 2 – $a = 3 \cdot 10^{-9}$, $b = -5 \cdot 10^{-7}$, $c = -2 \cdot 10^{-5}$, $d = 50 \cdot 10^{-4}$; 3 – $a = 7 \cdot 10^{-9}$, $b = -1 \cdot 10^{-6}$, $c = 7 \cdot 10^{-5}$, $d = 26 \cdot 10^{-4}$; and (f) 1 – $a = 8 \cdot 10^{-9}$, $b = -1 \cdot 10^{-6}$, $c = 3 \cdot 10^{-5}$, $d = 46 \cdot 10^{-4}$; 2 – $a = 5 \cdot 10^{-9}$, $b = -1 \cdot 10^{-6}$, $c = 2 \cdot 10^{-5}$, $d = 45 \cdot 10^{-4}$; 3 – $a = 2 \cdot 10^{-9}$, $b = -1 \cdot 10^{-6}$, $c = 2 \cdot 10^{-5}$, $d = 46 \cdot 10^{-4}$

of the time and rates of moisture release on the heating temperature. This is attributed to a number of factors. First, the exponential nature of curves for the liquid evaporation rates is consistent with known exponential dependences of evaporation rates on the heating temperature in convective, conductive and radiant heat exchange [16]. However, the values of these rates in the experiments [16] are severalfold higher than in this study. Second, the forest fuel sample is a porous frame in which water penetrates the material pores at different rates (when comparing pine needles and leaves) and to different depths [6].

The higher the heating temperature, the greater the depth from which the liquid leaves the sample in the form of vapors. Third, the higher the heating temperature, the greater the effect of two extra factors on the evaporation rate: release of internal moisture of the forest fuels and the thermal decomposition of material. They have a significant effect on the absorption of heat as a result of heat release and energy accumulation in the sample, as well as on the occlusion of pores with the gas-vapor mixture.

The comparison of curves and approximation equations for the instantaneous and average rates of moisture release shows that they are generally exponential, though the dependences of these rates on heating time are well described by a second order polynomial. This is because the effect of a group of temporally distributed factors, significant in the calculation of the instantaneous rates of phase transformations, is lessened when averaging the moisture

release rates. In particular, the instantaneous rates of moisture release are calculated for a certain time point. It was established that the moisture evaporation rates reach an asymptote after the sample is heated for a certain time. Its presence is explained by a gas-vapor mixture with a relatively low temperature, forming around the sample surface. It reduces the heat flux supplied directly to the material. Such mixture serves as a buffer layer between the material sample and the ambient heated air. That is why an exponential approximation equation can be used for the instantaneous evaporation rates.

The more empirical coefficients there are in the approximation, the more accurate the description. In this case, it is enough to use second order polynomials. Notably, asymptotic values of evaporation rates were not recorded in all the experiments. This was because the samples became denser at the initial point and more porous during heating as a result of moisture release. It can, thus, be concluded that the rates of moisture release are significantly affected by the density of the fuel sample.

Figure 4 presents the average mass rates of moisture release from forest fuel samples vs. heating temperature. Figure 5 shows the duration of moisture release from the material

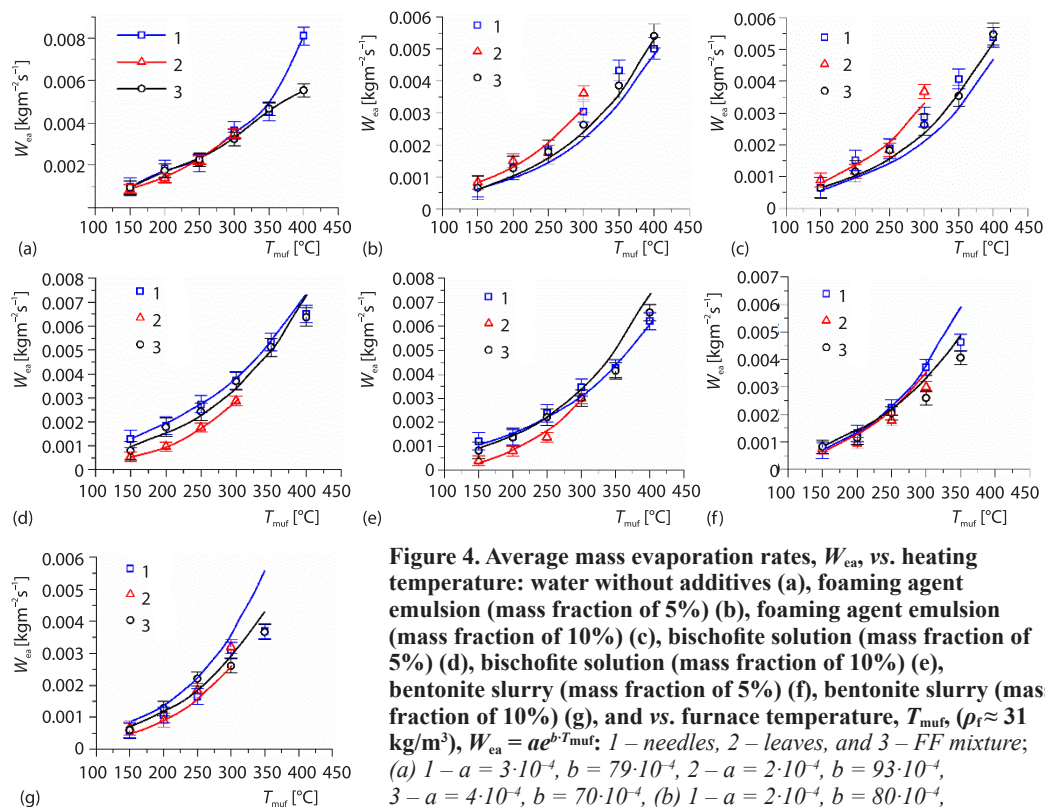


Figure 4. Average mass evaporation rates, W_{ea} , vs. heating temperature: water without additives (a), foaming agent emulsion (mass fraction of 5%) (b), foaming agent emulsion (mass fraction of 10%) (c), bischofite solution (mass fraction of 5%) (d), bischofite solution (mass fraction of 10%) (e), bentonite slurry (mass fraction of 5%) (f), bentonite slurry (mass fraction of 10%) (g), and vs. furnace temperature, T_{muf} , ($\rho_f \approx 31 \text{ kg/m}^3$), $W_{ea} = ae^{bT_{muf}}$; 1 – needles, 2 – leaves, and 3 – FF mixture; (a) $1 - a = 3 \cdot 10^{-4}$, $b = 79 \cdot 10^{-4}$, $2 - a = 2 \cdot 10^{-4}$, $b = 93 \cdot 10^{-4}$, $3 - a = 4 \cdot 10^{-4}$, $b = 70 \cdot 10^{-4}$, (b) $1 - a = 2 \cdot 10^{-4}$, $b = 80 \cdot 10^{-4}$, $2 - a = 2 \cdot 10^{-4}$, $b = 92 \cdot 10^{-4}$, $3 - a = 2 \cdot 10^{-4}$, $b = 82 \cdot 10^{-4}$, (c) $1 - a = 2 \cdot 10^{-4}$, $b = 79 \cdot 10^{-4}$, $2 - a = 2 \cdot 10^{-4}$, $b = 94 \cdot 10^{-4}$, $3 - a = 2 \cdot 10^{-4}$, $b = 82 \cdot 10^{-4}$, (d) $1 - a = 5 \cdot 10^{-4}$, $b = 67 \cdot 10^{-4}$, $2 - a = 1 \cdot 10^{-4}$, $b = 112 \cdot 10^{-4}$, $3 - a = 3 \cdot 10^{-4}$, $b = 80 \cdot 10^{-4}$, (e) $1 - a = 4 \cdot 10^{-4}$, $b = 68 \cdot 10^{-4}$, $2 - a = 6 \cdot 10^{-4}$, $b = 131 \cdot 10^{-4}$, $3 - a = 3 \cdot 10^{-4}$, $b = 80 \cdot 10^{-4}$, (f) $1 - a = 2 \cdot 10^{-4}$, $b = 97 \cdot 10^{-4}$, $2 - a = 2 \cdot 10^{-4}$, $b = 96 \cdot 10^{-4}$, $3 - a = 3 \cdot 10^{-4}$, $b = 80 \cdot 10^{-4}$, and (g) $1 - a = 2 \cdot 10^{-4}$, $b = 95 \cdot 10^{-4}$, $2 - a = 1 \cdot 10^{-4}$, $b = 109 \cdot 10^{-4}$, $3 - a = 2 \cdot 10^{-4}$, $b = 88 \cdot 10^{-4}$

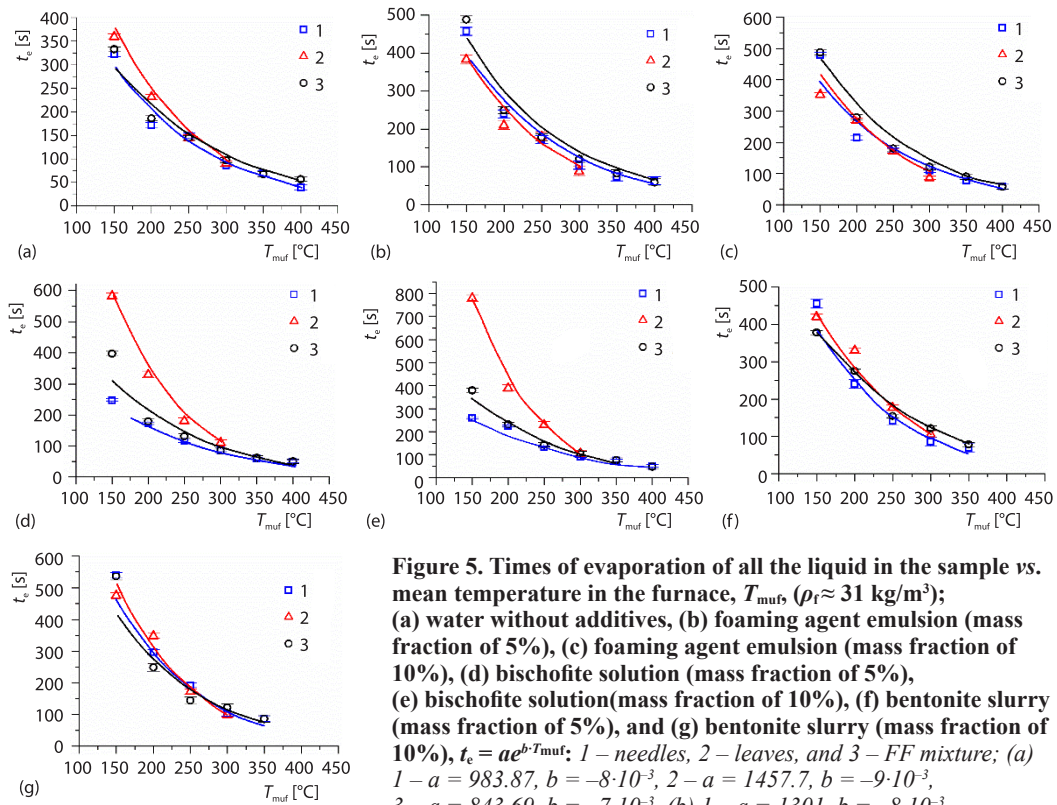


Figure 5. Times of evaporation of all the liquid in the sample vs. mean temperature in the furnace, T_{muf} ($\rho_f \approx 31 \text{ kg/m}^3$); (a) water without additives, (b) foaming agent emulsion (mass fraction of 5%), (c) foaming agent emulsion (mass fraction of 10%), (d) bischofite solution (mass fraction of 5%), (e) bischofite solution (mass fraction of 10%), (f) bentonite slurry (mass fraction of 5%), and (g) bentonite slurry (mass fraction of 10%), $t_e = ae^{b \cdot T_{muf}}$: 1 – needles, 2 – leaves, and 3 – FF mixture; (a) 1 – $a = 983.87$, $b = -8 \cdot 10^{-3}$, 2 – $a = 1457.7$, $b = -9 \cdot 10^{-3}$, 3 – $a = 843.69$, $b = -7 \cdot 10^{-3}$, (b) 1 – $a = 1301$, $b = -8 \cdot 10^{-3}$, 2 – $a = 1488$, $b = -9 \cdot 10^{-3}$, 3 – $a = 1450$, $b = -8 \cdot 10^{-3}$, (c) 1 – $a = 1305$, $b = -8 \cdot 10^{-3}$, 2 – $a = 1601$, $b = -9 \cdot 10^{-3}$, 3 – $a = 1541$, $b = -8 \cdot 10^{-3}$, (d) 1 – $a = 643.45$, $b = -7 \cdot 10^{-3}$, 2 – $a = 3103.2$, $b = -11 \cdot 10^{-3}$, 3 – $a = 1046.5$, $b = -8 \cdot 10^{-3}$, (e) 1 – $a = 755$, $b = -7 \cdot 10^{-3}$, 2 – $a = 5570.8$, $b = -13 \cdot 10^{-3}$, 3 – $a = 1169.8$, $b = -8 \cdot 10^{-3}$, (f) 1 – $a = 1734.8$, $b = -1 \cdot 10^{-2}$, 2 – $a = 1936.5$, $b = -1 \cdot 10^{-2}$, 3 – $a = 1262.2$, $b = -8 \cdot 10^{-3}$, (g) 1 – $a = 2080.6$, $b = -1 \cdot 10^{-2}$, 2 – $a = 2647.5$, $b = -11 \cdot 10^{-3}$, 3 – $a = 1622.6$, $b = -9 \cdot 10^{-3}$

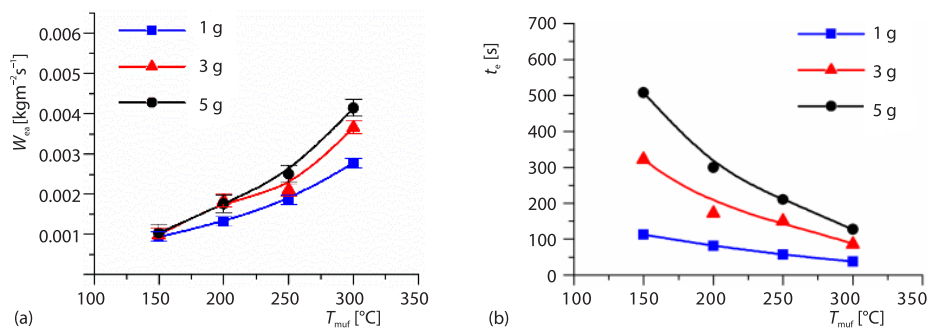


Figure 6. Mean mass rates of evaporation, W_{ea} , of water from the surface of needle (a) and time of evaporation, t_e , of all the liquid from the sample (b) vs. mean ambient temperature; $W_{ea} = ae^{b \cdot T_{amb}}$: 1 – 1 g, 2 – 3 g, and 3 – 5 g; (a) 1 – $a = 3 \cdot 10^{-4}$, $b = 72 \cdot 10^{-4}$, 2 – $a = 3 \cdot 10^{-4}$, $b = 82 \cdot 10^{-4}$, 3 – $a = 3 \cdot 10^{-4}$, $b = 90 \cdot 10^{-4}$ and (b) 1 – $a = 331.81$, $b = -7 \cdot 10^{-3}$, 2 – $a = 1033.4$, $b = -8 \cdot 10^{-3}$, 3 – $a = 1927.7$, $b = -9 \cdot 10^{-3}$

samples, when varying the heating temperature. Figure 6 presents the average mass rates of moisture release *vs.* heating temperature for various masses of the liquid.

The differences in the rates of moisture release, obtained for four liquid compositions (water, slurries, emulsions, and solutions), are primarily conditioned by different patterns of their movement through the layers of the forest materials under study. This research advances the formulated hypotheses [6] for water droplets of different dimensions, penetrating the deep layers of the samples of leaves and pine needles. If we average the rates of moisture release, obtained in this study for various component compositions, and range them from maximum to minimum, the liquids under study will be arranged in the following order: water, bischofite solutions, bentonite emulsions, foaming agent emulsions. The thermal and physical properties of the liquid compositions suggest that bentonite slurries should be the first to heat up. This is because the thermal diffusivity and conductivity of liquid compositions increase significantly, when solid particles are added. Moreover, the thermal radiation absorptivity rises substantially as compared with the slurry of water without additives. The next in descending order should be foaming agent emulsions, as they feature much lower surface tension.

Moreover, the experiments showed that the droplets of emulsions were much smaller than those of other compositions, which was also because their surface tension was lower than that of water. Thus, they were supposed to heat up and evaporate faster when the sample was heated. However, the experiments revealed that the recorded trends for the rates of moisture release from the samples with various liquid compositions looked different. They can be explained by using the results of recording the movement of liquid composition droplets in the layers of the forest fuel sample. The technique [6] was applied. It was found that the movement of the bentonite slurry and foaming agent emulsion droplets differed significantly from that of water and the bischofite solutions. The rates of moisture release for the latter are generally close. Higher heating and evaporation rates of water, as compared with the solutions, can be explained by greater heat capacity of the liquid composition as a result of adding salt. Thus, less energy is absorbed in the phase transition. Unlike water and the solutions, the bentonite slurry significantly densifies the near-surface layer of the sample, thus, slowing down the movement of liquid into the deeper layers. The porous frame of the sample in the near-surface layers becomes almost monolithic (continuous). This complicates the release of moisture. The foaming agent emulsions, on the contrary, spread over the sample surface and into the deep layers due to much lower surface tension. Thus, the free surface of the material is almost completely covered in the emulsion. This slows down the heating of the material frame as a result of heat exchange with the external environment. The energy is supplied to the deeper layers, and it takes more time for moisture to be released. The experimental video frames also showed that the emulsion droplets, when heated, did not decrease steadily but there was a distinctive collapse of bubbles. Thus, the dimensions of droplets increased at the first stage as they were filled with vapors. After that, they abruptly decreased as the bubbles collapsed. A hypothesis can be formulated that these processes also slow down the release of moisture from the deep layers of the material sample.

We analyzed how the type of forest fuel affected the rates of moisture release. The findings for the said compositions indicate a shift of the experimental curves for pine needles and leaves relative to each other, *i.e.*, the maximum rates of heating and moisture release differed for various component compositions when using different fuels. The duration of moisture removal, the instantaneous and mean rates of moisture release were average for the mixture of forest fuels as compared with the same parameters of pine needles and leaves. The main reasons for the differences in the evaporation rates of the four liquid compositions (water, solutions,

slurries and emulsions) are different patterns of their interaction with pine needles, leaves and a mixture of forest fuels. Hydrophilic and hydrophobic properties in the zone of the liquid composition contact with the fuels play a significant part, too. When they have contact with leaves, most of the water is slowed down in the near-surface layers and densifies them. The analysis of similar experimental frames with pine needles shows that most of the liquid penetrates into deep layers. The findings suggest that the characteristics under study (evaporation rates) for other forest fuel types (*e.g.*, branches, bark, grass, *etc.*) may differ significantly from those obtained in this study. Thus, the findings for pine needles, leaves and a mixture of materials are not the same as for other types of biomass.

The established patterns of liquid spreading over the surface of the sample and in its porous structure allow us to conclude that one of the promising objectives for future research would be to take into account the surface area of the material from which the liquid evaporates (*i.e.*, when considering the interstitial surface of evaporation of deep layers). The major challenge is to adequately estimate this parameter, since the sizes of pores in the material sample differ by their depth and transverse sections. Moreover, they are filled with liquid and with thermal decomposition products at the start of the experiment, when heated rapidly. Such estimation is possible using the results of high speed video recording and thermocouple measurements in deep layers, employing a technique similar to [6]. At a first approximation, a hypothesis can be formulated, using the data [6], that the surface areas of the phase transition – evaporation can increase by at least 15-35%. The evaporation rates (instantaneous and average) will change in the respective range.

When generalizing the research findings, one can formulate hypotheses about combined influence of four main factors (sizes of forest fuel structure elements, internal bound moisture of the material, stacking density in the sample, method of liquid supply) on the evaporation rates when using various schemes of liquid supply to the sample. Current fire extinguishing systems rely on three typical techniques of liquid supply: local discharge (without spraying). Atomization of droplets using spray nozzles; burst injection of liquid droplets as aerosol. The analysis of the findings [4-6] indicates that the highest rates of moisture release correspond to the third scheme of liquid supply to the sample. The lowest ones correspond to the first scheme that does not involve any preliminary spraying of liquid. This is explained by the fact that the falling volume of liquid displaces a certain fraction of fuel from the sample, producing a funnel and letting moisture penetrate into deep layers.

The rate at which it is released from such layers is significantly lower than when it is released from the free surface, using the experimental heating scheme. The conditions can be different in the thermal decomposition of deep layers. Thus, it is difficult to use (vaporize) the full volume of the liquid when applying this method of supplying it to the forest fuel layer. The initial density of element stacking in the sample and its changes during the interaction with the supplied liquid play an important role, too. The higher the density of the sample, the more liquid will be retained on its surface and in the near-surface layers. Under such conditions, the rates of moisture release cannot be high. Similar patterns can be observed in the experiments with the growth of the internal moisture of the material (*i.e.*, its initial moisture content).

The size of forest fuel structure elements may be a contributing factor as well. The smaller the elements, the denser the frame. As a result, it is more difficult for the moisture supplied from outside to penetrate the sample pores and for the internal moisture to leave the deep layers. Thus, it can be concluded that all the four factors mentioned previously (sizes of forest fuel structure elements, internal bound moisture of the material, stacking density in the sample, method of liquid supply) can have a significant effect on the rates of moisture release from

forest fuels when heated. It is worthwhile to explore them to determine the efficient conditions of retention and, on the contrary, release of moisture from forest fuels during heating. This task becomes especially important with a rising interest in control lines as an effective means of forest fuel fire containment when a woodland layer is wetted ahead of the flame combustion and thermal decomposition fronts. Their main purpose is to prevent the spread of these fronts. Therefore, it makes sense to increase the time of moisture release from these layers when they are rapidly heated. In this case, a positive effect will be produced not only by the moisture in the deep layers of the material, but also by the vapor buffer zone above the control line surface. Solving these problems will increase the efficiency of high potential systems of fire extinguishing and combustion containment of forest fuels [17-20].

The efficiency of moisture release from the porous structure of forest fuels used as a control line has a significant influence on wildfire containment as a result of retarding (or completely stopping) the advancement of the combustion front over the material surface, since the combustion of forest fuels is quite unsteady. When the forest fuel combustion front is contained, no new portions of combustible materials are involved in thermal decomposition and subsequent flame combustion. Over time, this substantially reduces the inflow of gaseous products of forest fuel (main fuel) pyrolysis to the combustion zone, the total heat supply, the flame height and the heat flux from the combustion area to the forest fuel surface in the initial state. Even if it is impossible to completely stop the fire front, its movement rate can be significantly reduced, making forest fuel fires much easier to contain.

Conclusions

The experimental research findings allowed us to establish the range of the rates of moisture release from a group of typical forest fuels containing fire extinguishing agents in their layers. These conditions correspond to the release of moisture from forest fuels when using control lines in the form of wetted forest fuel layers. The rate of moisture release from the forest fuel sample increased by 3-5 times when the temperature grew from 150-400 °C.

The experiments with pine needles featured the highest moisture release rates, which was due to a much larger surface area over which the liquid was spreading. This effect was identified in the experiments and is also based on the conclusions [4-6]. The comparison of the fire extinguishing agents showed that the rates of moisture release were minimum for the slurries, average for the solutions, and maximum for water and the foaming agent emulsions. The most valuable scientific findings of the experiments consist in obtaining the curves for which the approximation equations were derived.

The research findings are applicable to forest litter (*i.e.*, not live plants) and can be used in aircraft fire suppression when creating control lines by supplying liquid from airplanes [17, 18], for instance, in water mist technologies and [19, 20]. Such control lines are used to fight big fires and prevent the spread of fire over large areas.

The following main approximation equations can be highlighted as common for the forest fuels and fire extinguishing agents under study:

- rates of moisture release over the heating time $W_{ei} = at^3 + bt^2 + ct + d$,
- rates of moisture release in the temperature range of 150-400 °C $W_{ea} = ae^{b \cdot T_{muf}}$, and
- time of moisture release in the temperature range of 150-400 °C $t_e = ae^{b \cdot T_{muf}}$.

The obtained approximation equations will make it possible to predict the conditions of long-lasting moisture retention in the layers of the material ahead of pyrolysis and flame combustion fronts for various fire extinguishing agents and forest fuels.

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Nomenclature

H – height, [mm]
 L – length, [mm]
 m – mass, [g]
 N – width, [mm]
 R – radius, [mm]
 S – area, [m²]
 T – temperature, [°C]
 t – time, [s]
 W – mass rate, [kgm⁻²s⁻¹]

Greek symbol

ρ – density, [kgm⁻³]

Subscripts

a – average
d – droplet
e – evaporation
f – sample
i – instantaneous
muf – muffle
sub – cuvette

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