

HEAT AND MASS TRANSFER IN QUENCHING THE REACTION OF THERMAL DECOMPOSITION OF A FOREST COMBUSTIBLE MATERIAL WITH A GROUP OF WATER DROPS

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We have carried out computational investigations of the processes of heat and mass transfer in quenching the reaction of thermal decomposition of the typical forest combustible materials (birch leaves and pine and fir needles) with a group of water drops. It has been established that the termination time of pyrolysis is influenced by the integral parameter characterizing the relative position of drops and the temperature of the vapor-gas mixture over the forest combustible material. The thicknesses of layers providing termination of pyrolysis of evaporated liquid materials for a group of drops have been determined.

Keywords: *heat and mass transfer; thermal decomposition, forest combustible, near-surface heated layer, water, drops.*

Introduction. In spite of the extensive recent investigations of fire hazard forecast methods [1–3] and the processes of heat and mass transfer proceeding during combustion of forest combustible materials (FCM) [4–6], the problem of forest fires remains unsolved.

Analytical [7–11], numerical [12, 13], and experimental [14–16] investigations have shown that the efficiency of using water in the process of quenching such fires can be increased if it is sprayed finely in the flame zone of combustion. It has been established [7–16] that it is expedient to convey into the combustion zone water or its mixtures with various additives (retardants, phlegmatizers, etc.) in the form of a large group of drops with conditional sizes from 50 to 500 μm . The liquid dispersion is determined by the height of the flame and its average temperature [11–16]. Such atomization of water provides intense vaporization. Practically the whole of the water evaporates in the flame zone of combustion, forming a vapor-gas mixture with a rather low temperature of 300–450 K [12–14]. Only a small portion of the liquid reaches the surface of burning substances and materials. In the near-surface layer, where the reaction takes place in the process of combustion of materials, there are, as a rule, large heat stores (especially in the case of forest fires). In order to quench the reaction of thermal decomposition of the typical forest combustible materials, it seems necessary to estimate the sufficient size of water drops and their relative position on the FCM surface, as well as the parameters of the external vapor-gas mixture (in particular, the temperature). It is practically impossible to carry out pertinent experimental investigations under real fire conditions. Performing experiments under laboratory conditions may lead to considerable deviations of obtained results from the real conditions. Therefore, it is expedient to carry out computational modeling of a complex of interrelated heat and mass transfer processes in the FCM system water drops–vapor-gas mixture with the use of modern approaches and methods, for example, as in [17–19], in order to determine the thickness of the evaporated liquid layer, the characteristic time of termination of the thermal decomposition reaction, as well as the influence of the ambient conditions on the integral heat and mass transfer parameters.

The aim of the present work is to carry out computational modeling of the heat and mass transfer processes in quenching the reaction of thermal decomposition of the typical forest combustible materials (birch leaves and pine and fir needles) with a group of drops.

Formulation of the Problem. In formulating the problem, we assumed that a "water slug" (a large aggregate of water drops) has passed through the flame and has partially evaporated. Only a small group of drops has reached the surface of the thermally decomposing FCM. In the general case, various distances are possible between individual drop of water on the surface of the rapidly pyrolyzed FCM. In spite of its high porosity, the FCM surface represents fragments of solid thermal

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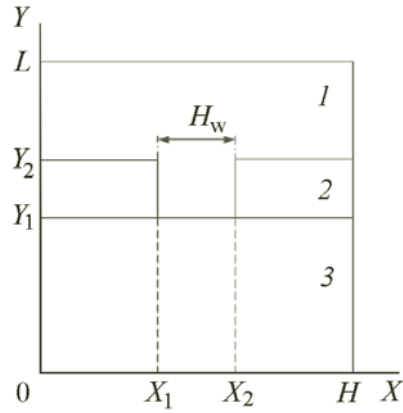


Fig. 1. Scheme of the problem solution domain: 1) vapor-gas mixture; 2) water drop; 3) FCM.

decomposition products on which individual drops can fall (and get fixed due to the wetting effect). The permeation of water into the FCM structure will also be inhibited to a certain extent by the gaseous products of the thermal decomposition of the forest combustible material filtering to the heating surface. Of the variety of possible positions of a group of drops on the FCM surface, the variant of two drops spaced a certain distance apart ($H_w = X_2 - X_1$) is the most significant for the subsequent analysis (Fig. 1). All the other schemes are modifications of the variant of two neighboring drops; therefore, in formulating the problem, we considered the solution domain scheme presented in Fig. 1.

We assumed that the liquid was heated due to the heat exchange with the thermally decomposing FCM. At all boundaries of water drops, when proper conditions are attained, vaporization (evaporation) occurs. Due to the heat of the endothermal phase transition and the conductive heat exchange, the FCM temperature decreases.

From the results of the computational modeling, the time τ_d of the FCM temperature drop to the temperature of the beginning of thermal decomposition Θ_d was determined. The τ_d value illustrates the quenching (termination) time of the thermal decomposition reaction of the FCM.

Mathematical Model and Solution Methods. The nonlinear nonstationary differential heat and mass transfer equations in partial derivatives in dimensionless variables for the system FCM–water drops–vapor-gas mixture (Fig. 1) at $0 < \tau < \tau_d$ have the following form:

the energy equation for the FCM ($0 < X < H, 0 < Y < Y_1$)

$$\frac{1}{\text{Fo}_3} \frac{\partial \Theta_3}{\partial \tau} = \frac{\partial^2 \Theta_3}{\partial X^2} + \frac{\partial^2 \Theta_3}{\partial Y^2} + \text{Sr}_3, \quad (1)$$

the equation of the chemical reaction in the heated FCM layer ($0 < X < H, 0 < Y < Y_1$)

$$\frac{d\varphi_3}{dt} = (1 - \varphi_3) k_3^0 \exp\left(-\frac{E_3}{RT_3}\right), \quad (2)$$

the heat conduction equation for water drops ($0 < X < X_1, X_2 < X < H, Y_1 < Y < Y_2$)

$$\frac{1}{\text{Fo}_2} \frac{\partial \Theta_2}{\partial \tau} = \frac{\partial^2 \Theta_2}{\partial X^2} + \frac{\partial^2 \Theta_2}{\partial Y^2}, \quad (3)$$

the energy equation for the vapor-gas mixture ($X < X_1 < X_2, Y_1 < Y < Y_2, 0 < X < H, Y_2 < Y < L$)

$$\frac{1}{\text{Fo}_1} \frac{\partial \Theta_1}{\partial \tau} = \frac{\partial^2 \Theta_1}{\partial X^2} + \frac{\partial^2 \Theta_1}{\partial Y^2}, \quad (4)$$

the diffusion equation of thermal decomposition products of the FCM ($X_1 < X < X_2, Y_1 < Y < Y_2, 0 < X < H, Y_2 < Y < L$)

$$\frac{\partial C_f}{\partial \tau} = \text{Gp}_{11} \left(\frac{\partial^2 C_f}{\partial X^2} + \frac{\partial^2 C_f}{\partial Y^2} \right), \quad (5)$$

the diffusion equation of water vaporization products ($X_1 < X < X_2, Y_1 < Y < Y_2, 0 < X < H, Y_2 < Y < L$)

$$\frac{\partial C_v}{\partial \tau} = \text{Gp}_{12} \left(\frac{\partial^2 C_v}{\partial X^2} + \frac{\partial^2 C_v}{\partial Y^2} \right), \quad (6)$$

$$\text{Fo}_1 = \frac{\lambda_1 t_m}{\rho_1 C_1 l_m^2}, \quad \text{Fo}_2 = \frac{\lambda_2 t_m}{\rho_2 C_2 l_m^2}, \quad \text{Fo}_3 = \frac{\lambda_3 t_m}{\rho_3 C_3 l_m^2}, \quad \text{Gp}_{11} = \frac{D_{11} t_m}{l_m^2}, \quad \text{Gp}_{12} = \frac{D_{12} t_m}{l_m^2}, \quad \text{Sr}_3 = \frac{Q_3 W_3 l_m^2}{\lambda_3 \Delta T},$$

$$\Delta T = T_m - T_w.$$

The initial conditions ($\tau = 0$) are as follows (Fig. 1): $\Theta = \Theta_0(X, Y)$ at $0 < X < H, 0 < Y < Y_1$; $\Theta = \Theta_w$ at $0 < X < X_1, X_2 < X < H, Y_1 < Y < Y_2$; $\Theta = \Theta_f, C_v = 0, C_f = 0$ at $X_1 < X < X_2, Y_1 < Y < Y_2, 0 < X < H, Y_2 < Y < L$.

The boundary conditions at $0 < \tau \leq \tau_d$ (Fig. 1) are as follows:

$$X = 0, \quad X = H, \quad 0 < Y < Y_1, \quad \frac{\partial \Theta_3}{\partial X} = 0, \quad (7)$$

$$X = 0, \quad X = H, \quad Y_1 < Y < Y_2, \quad \frac{\partial \Theta_2}{\partial X} = 0, \quad (8)$$

$$X = 0, \quad X = H, \quad Y_2 < Y < L, \quad \frac{\partial \Theta_1}{\partial X} = 0, \quad \frac{\partial C_v}{\partial X} = 0, \quad \frac{\partial C_f}{\partial X} = 0, \quad (9)$$

$$Y = 0, \quad 0 < X < H, \quad \frac{\partial \Theta_3}{\partial Y} = 0, \quad (10)$$

$$Y = Y_1, \quad 0 < X < X_1, \quad X_2 < X < H, \quad -\frac{\partial \Theta_3}{\partial Y} - \frac{l_m(Q_3 W_3^\Sigma + Q_2 W_2)}{\lambda_3 \Delta T} = -\frac{\lambda_2}{\lambda_3} \frac{\partial \Theta_2}{\partial Y}, \quad (11)$$

$$Y = Y_1, \quad X_1 < X < X_2, \quad -\frac{\partial \Theta_3}{\partial Y} - \frac{l_m Q_3 W_3^\Sigma}{\lambda_3 \Delta T} = -\frac{\lambda_1}{\lambda_3} \frac{\partial \Theta_1}{\partial Y}, \quad \frac{\partial C_f}{\partial Y} = \frac{W_3^\Sigma l_m}{\rho_{11} D_{11}} \frac{\partial C_v}{\partial Y} = 0, \quad (12)$$

$$X = X_1, \quad X = X_2, \quad Y_1 < Y < Y_2, \quad -\frac{\partial \Theta_2}{\partial X} - \frac{l_m Q_2 W_2}{\lambda_2 \Delta T} = -\frac{\lambda_1}{\lambda_2} \frac{\partial \Theta_1}{\partial X}, \quad \frac{\partial C_v}{\partial X} = \frac{W_2 l_m}{\rho_{12} D_{12}}, \quad \frac{\partial C_f}{\partial X} = 0, \quad (13)$$

$$Y = Y_2, \quad 0 < X < X_1, \quad X_2 < X < H, \quad -\frac{\partial \Theta_2}{\partial Y} - \frac{l_m Q_2 W_2}{\lambda_2 \Delta T} = -\frac{\lambda_1}{\lambda_2} \frac{\partial \Theta_1}{\partial Y}, \quad \frac{\partial C_v}{\partial Y} = \frac{W_2 l_m}{\rho_{12} D_{12}}, \quad \frac{\partial C_f}{\partial Y} = 0, \quad (14)$$

$$Y = L, \quad 0 < X < H, \quad \frac{\partial^2 \Theta_2}{\partial Y^2} = 0, \quad \frac{\partial^2 C_v}{\partial Y^2} = 0, \quad \frac{\partial^2 C_f}{\partial Y^2} = 0. \quad (15)$$

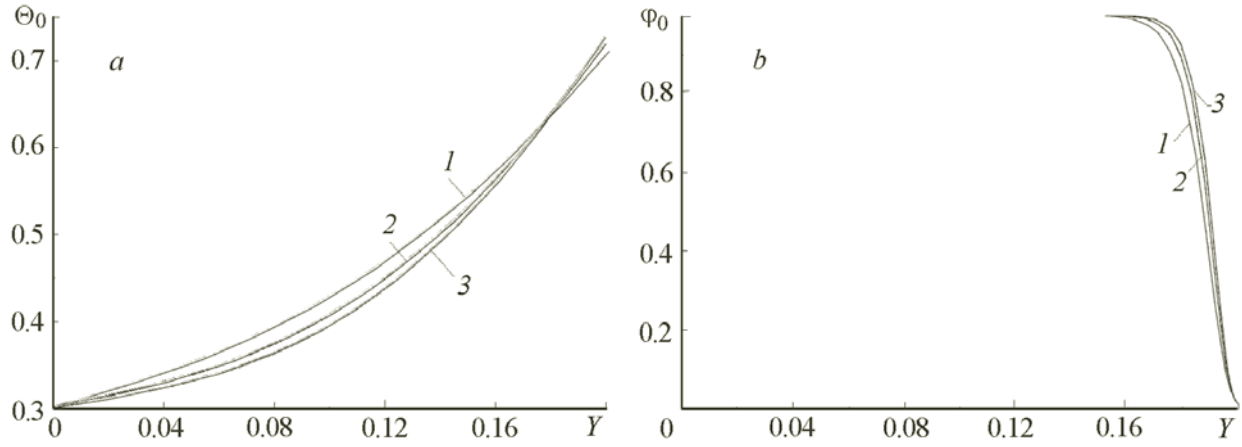


Fig. 2. Distributions of the temperature (a) and the fraction of the chemically reactive substance (b) in the FCM ($L_w = 0.2$) under its thermal decomposition at a constant ambient temperature ($\Theta = 1.17$) at $X = X_1 + 0.5(X_2 - X_1)$: 1) birch leaves; 2) pine needles; 3) fir needles.

To determine the initial distributions of the temperature $\Theta_0(X, Y)$ and the fraction of the chemically reactive (thermally decomposable) substance $\phi_0(X, Y)$ in the near-surface layer of the FCM (of thickness L_f) for investigating the heat and mass transfer (Fig. 1), we solved the problem of [20–23]. We calculated the distributions $\Theta_0(X, Y)$ and $\phi_0(X, Y)$ [20–23] at a certain instant of time at a constant temperature of the gaseous environment (combustion products), $\Theta = 1.17$, corresponding to the average fire temperature [24]. The initial temperatures of the water drops Θ_w and the vapor-gas mixture Θ_f were assumed to be constant. Figure 2 shows the typical (initial for the formulated problem) distributions $\Theta_0(X)$ and $\phi_0(X)$ at $Y = 0.5$ in the FCM obtained in solving the heat transfer problem under its combustion conditions [20–23].

The mass rate of evaporation of the liquid was calculated by the formula [25]

$$W_2 = \frac{\beta}{1 - k_\beta \beta} \frac{(P^n - P)}{\sqrt{2\pi RT_{2s}/M}}.$$

The dimensionless parameters β and k_β were taken to be equal to 0.1 and 0.4 in accordance with the results of investigations made in [25, 26]. To calculate the thermal decomposition rate of the FCM, we used the expression [27]

$$W_3 = \phi_3 \rho_3 k_3^0 \exp\left(-\frac{E_3}{RT_3}\right).$$

The pressure of water vapors was calculated by the Clapeyron–Mendeleev equation [28].

To take into account the injection of water vapors and thermal decomposition products into the gaseous region from under the drops, the algorithms and methods described in [29, 30] were used. The thermal characteristics of the FCM were calculated with account for the pyrolysis:

$$\lambda_3 = \lambda_{31}\phi_3 + \lambda_{32}(1 - \phi_3),$$

$$C_3 = C_{31}\phi_3 + C_{32}(1 - \phi_3),$$

$$\rho_3 = \rho_{31}\phi_3 + \rho_{32}(1 - \phi_3).$$

Likewise, the thermal characteristics of the mixture of water vapors and gaseous pyrolysis products were calculated in accordance with the values of concentrations C_v and C_f .

To turn to dimensionless variables, we used the following values as the scale ones: $l_m = 0.1$ m, $t_m = 1$ s, $T_m = 1000$ K.

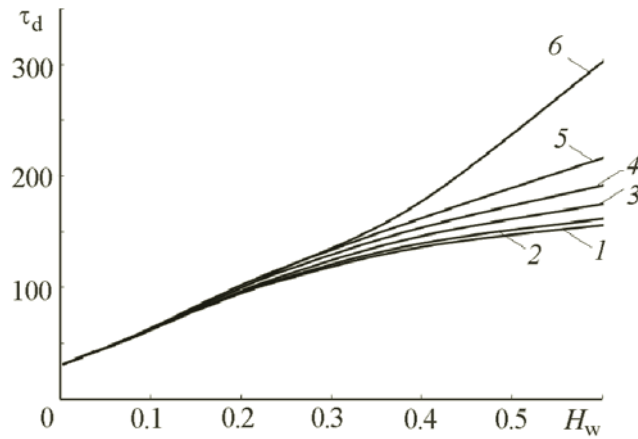


Fig. 3. Quenching times of the reaction of chemical decomposition of the FCM (pine needles) versus the parameter H_w at various temperatures in the wake of the "water slug" and $L_f = 0.4$: 1) $\Theta_f = 0.3$, 2) 0.35, 3) 0.45, 4) 0.55, 5) 0.65, 6) 0.8.

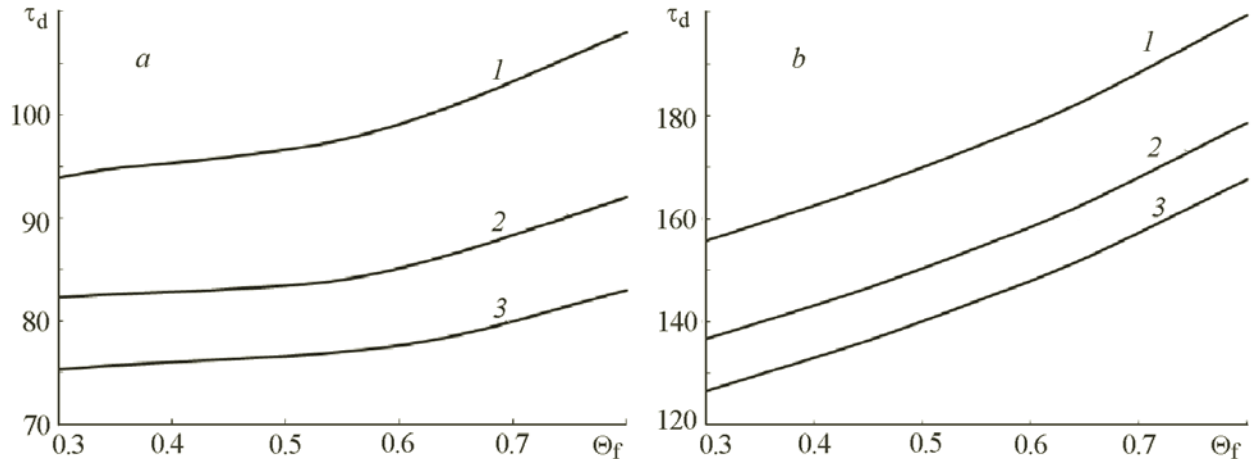


Fig. 4. Quenching times of the reaction versus the temperature in the wake of the "water slug" Θ_f at $L_f = 0.4$, $H_w = 0.15$ (a) and 0.4 (b): 1) birch leaves; 2) pine needles; 3) fir needles.

The system of nonstationary differential equations (1)–(15) was solved by the finite difference method [31]. The difference analogs of the differential equations (1)–(15) were solved by the local-one-dimensional method [31]. To solve the one-dimensional difference equations, we used the sweep method with the use of the implicit four-point scheme [31]. The nonlinear equations were solved by the iteration method [32]. To increase the accuracy of the solution of the system of differential equations (1)–(15), we used nonuniform time (10^{-4} – 10^{-2}) and coordinate (10^{-8} – 10^{-6}) steps. Near the phase transition boundaries the computational mesh was made finer by an algorithm analogous to [12].

The method for estimating the reliability of the results of the conducted theoretical investigations based on the check of conservatism of the used computational mesh is analogous to that used in [12, 13].

Results and Discussion. The computational investigations were carried out at the following values of the parameters [20–22, 33–36]: the initial temperature of water $\Theta_w = 0.3$ and of the vapor-gas mixture $\Theta_f = 0.3$ – 0.8 ; the temperature of the onset of thermal decomposition of the FCM $\Theta_d = 0.5$; the kinetic parameters of the chemical reaction were as follows: $k_0^3 = 3.63 \cdot 10^4 \text{ s}^{-1}$, $E_3 = 78.114 \text{ kJ/mole}$, $Q_3 = 1 \cdot 10^3 \text{ J/kg}$; the molar mass of water $M = 18 \text{ kg/mole}$; the thermal effect of water evaporation $Q_2 = 2.26 \text{ MJ/kg}$. The thickness of the heated layer of the FCM was chosen to be typical of forest fires $L_f = 0.04$ – 0.06 .

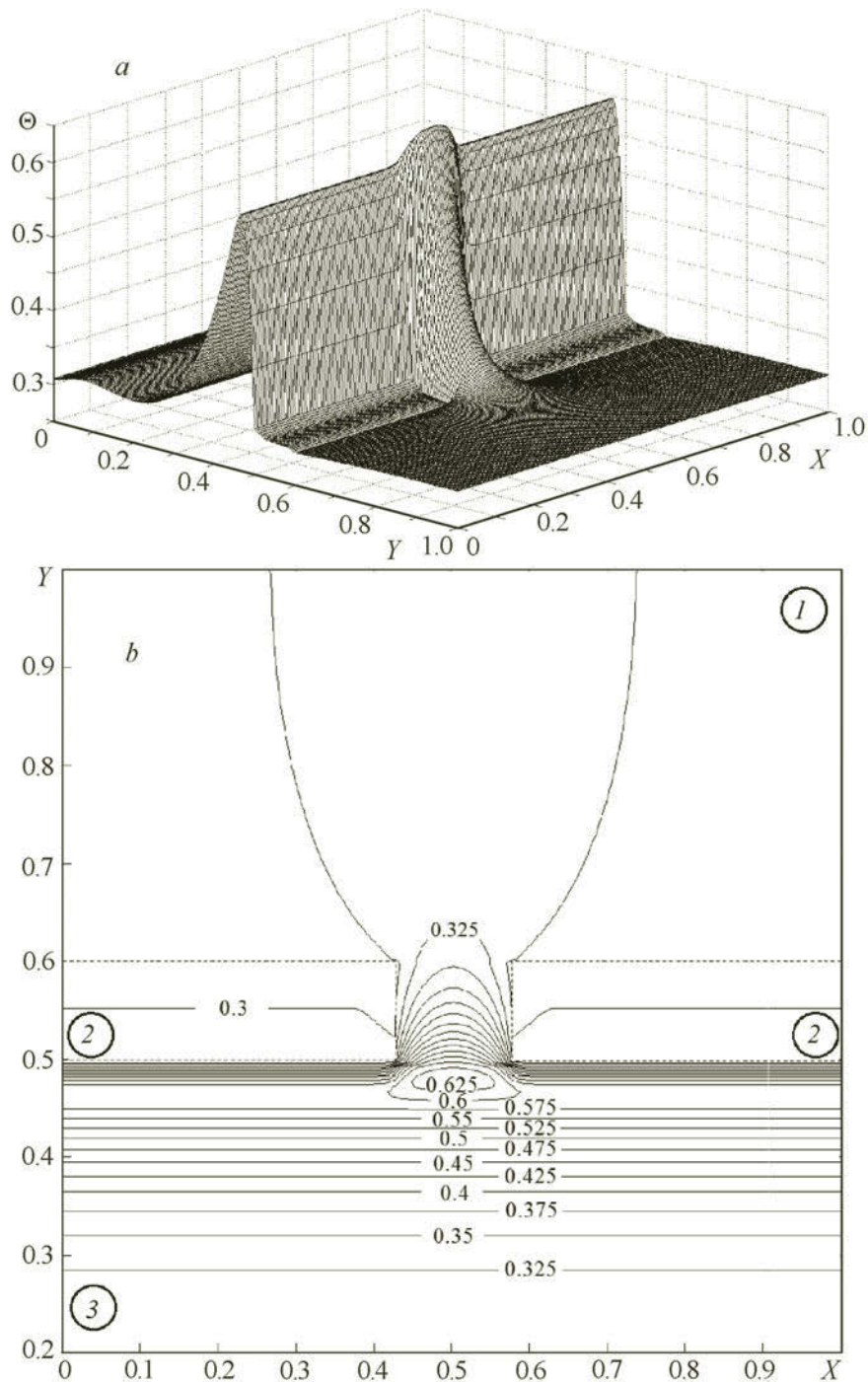


Fig. 5. Temperature field (a) and isotherms (b) in the system pine needles–water drops–vapor-gas mixture at $\Theta_f = 0.3$, $H_w = 0.15$, $L_f = 0.5$, $\tau = 10$: 1) vapor-gas mixture, 2) water drops, 3) FCM.

The longitudinal and transverse sizes of drops were $H_{dr} = 0.1–0.5$ and $L_{dr} = 0.1$. The distance between drops was varied over the range of $H_w = 0.01–0.9$. The characteristic sizes of the solution domain were varied depending on the values of H_{dr} , H_w , and L_f over the ranges of $H = 0.5–1$ and $L = 0.5–1$. The thermal characteristics of the FCMs (birch leaves and pine and fir needles), pyrolysis products, water, and water vapors were taken from [33–36]

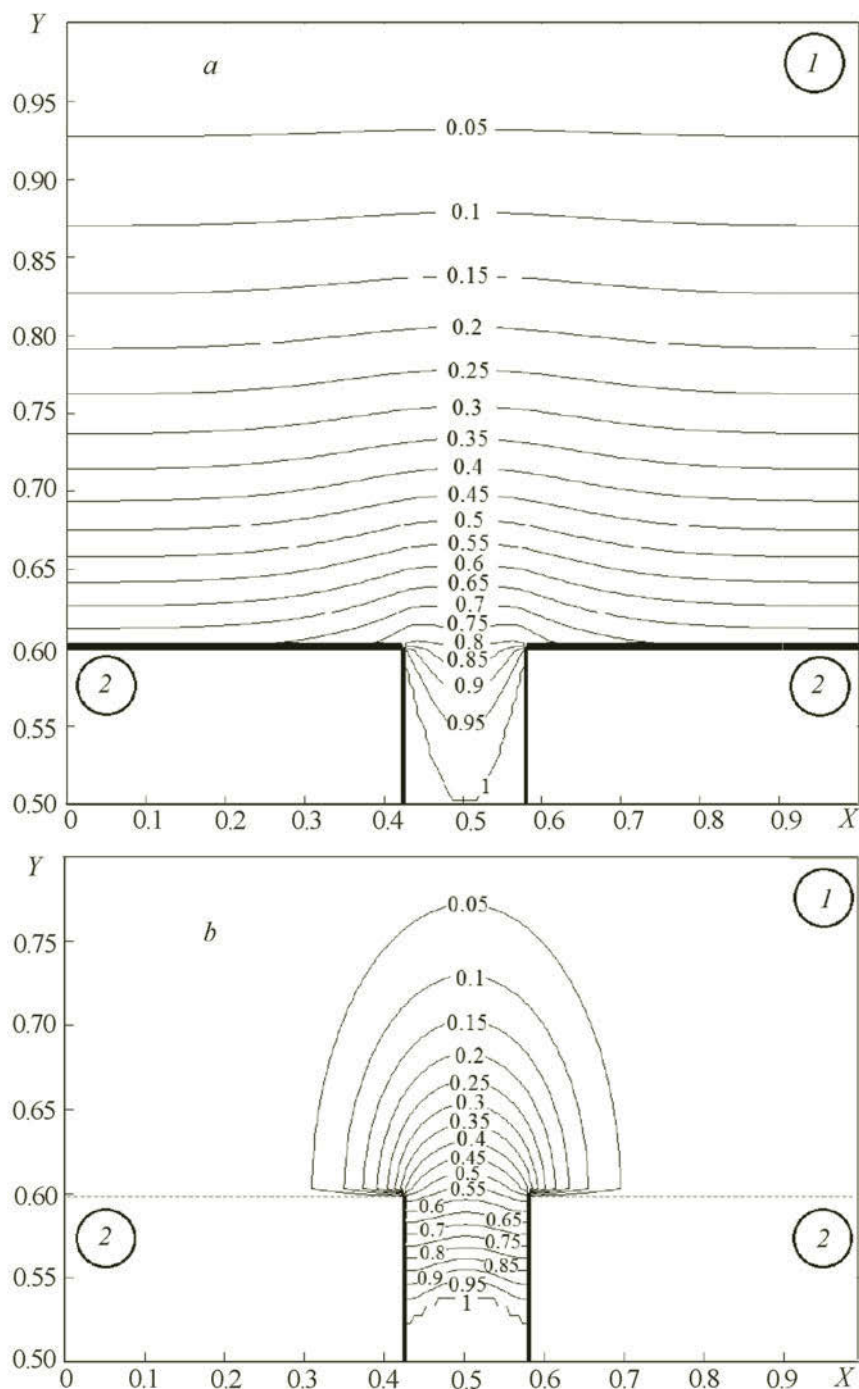


Fig. 6. Concentration isolines of water vapors (a) and pyrolysis products (b) in the system pine needles–water drops–vapor-gas mixture at $\Theta_f = 0.3$, $H_w = 0.15$, $L_f = 0.5$, $\tau = 10$: 1) vapor-gas mixture, 2) water drops, 3) FCM.

Figure 3 shows the dependences of the time of quenching (termination) of the thermal decomposition reaction of the typical FCM (pine needles) on the integral parameter H_w characterizing the relative position of two water drops on the surface of the material under consideration. It is seen that the times of termination of the thermal decomposition reaction τ_d decrease essentially nonlinearly with decreasing H_w . Here a change in the dynamics of the decrease in τ_d with the temperature of the

vapor-gas mixture can be noted. For example, at Θ_f values corresponding to the range of the typical "water slug" (0.3–0.45), the dependences $\tau_d = f(H_w)$ differ insignificantly (curves 1–3 are fairly close). But as Θ_f and the dimensionless distances H_w increase, curves 4–6 move apart significantly (Fig. 3). It should be noted that at $\Theta_f > 0.8$ and $H_w > 0.6$ the thermal decomposition reaction is not quenched ($\tau_d \rightarrow \infty$). At $H_w < 0.2$ curves 1–6 practically join together. This result shows that even at fairly high temperatures of the surrounding gaseous medium, conditions for quenching the thermal decomposition reaction are created. The value of $H_w = 0.2$ can be considered to be the maximum value (the upper boundary) at which the vaporization of two "neighboring" water drops suffices for the thermal decomposition reaction of the FCM to terminate throughout the range of possible Θ_f values in practically equal times τ_d .

Figure 4 shows the dependences of the quenching time of the thermal decomposition reaction of the three most typical FCMs (birch leaves and pine and fir needles) on the temperature Θ_f in the considered system at $H_w = 0.15$ and $H_w = 0.4$. It is seen that the functions $\tau_d = f(\Theta_f)$ are also essentially nonlinear, which is due to both the chemical reaction in the near-surface layer of the FCM and the rapid vaporization.

The established dependences $\tau_d = f(\Theta_f)$ and $\tau_d = f(H_w)$ can be explained by the fact that in the region between drops, because of the intense heat release (by the thermal decomposition of the FCM), the temperature of the vapor-gas mixture increases considerably (Fig. 5). At relatively short distances between drops ($H_w = 0.2$) a large portion of this heat is expended in the vaporization from the lateral boundaries ($X = X_1, X = X_2, Y_1 < Y < Y_2$) of drops (because of the high thermal effect of liquid vaporization — $Q_2 = 2.26$ MJ/kg). In this case, the heating region of the vapor-gas mixture is limited by the thickness of the liquid drops (Fig. 5). However, with increasing H_w values, the characteristic sizes of the heating region of the vapor-gas mixture increase markedly. As a consequence, the termination time of the thermal decomposition reaction also increases (Fig. 3).

It should be noted that at intense vaporization the linear injection rates of water vapors into the surrounding gaseous medium increase. Figure 6 shows the concentration isolines of water vapors and gaseous pyrolysis products of the FCM at $\tau = 10$. It has been found that at $1 < \tau < 3$ the mass thermal decomposition rate W_3 is much higher than the vaporization rate W_2 . Since in the real wake of the "water slug" there is practically no oxidizer in free form [12, 13], the process of injection of pyrolysis products into the gas phase causes no acceleration of their oxidation reaction. Consequently, the chemical reaction does not lead to the formation of a region of intense heat release. This leads to inertial cooling of both the gaseous phase and the near-surface layer of the FCM (Fig. 5). As the duration of the process increases, the W_3 values decrease markedly (because of the FCM cooling), and at $\tau > 5$ they become smaller than the W_2 values (the vaporization rates practically hold constant their maximum values at $0 < \tau < \tau_d$, since the temperature at the water–FCM interface does not drop below the highest possible temperature of the phase transformation $\Theta = 0.37$). As a consequence, the concentration of water vapors C_v increases several times faster than that of the gaseous pyrolysis products C_f (Fig. 6). With further increase in the times of realization of the processes under consideration, the mass injection rates of pyrolysis products decrease (due to the cooling of the FCM). At the moment of completion of the reaction of thermal decomposition of the material, the concentrations of water vapors C_v exceed several times the corresponding C_f values. It may be concluded that even in the presence of an FCM surface not covered with liquid drops, practically the entire gas region over it is filled with water vapors.

As a result of the numerical investigations, it has established that at quenching times of the thermal decomposition reaction of up to $\tau_d = 50$ the thickness of the evaporated liquid layer does not exceed 1 mm. At the largest possible quenching times of the chemical reaction of the FCM ($\tau_d = 200$ – 300) the thickness of the evaporated layer of water reaches 1.5–2 mm. For "monolithic" water films (at $H_w = 0$) this value is less than 0.1 mm at $\tau_d < 30$. The obtained result shows that in the process of quenching of the chemical reaction in the heated layer of the FCM a small mass fraction of the water drops under consideration is active. Since with decreasing τ_d (for example, due to the decrease in Θ_f of H_w) the thickness of the evaporated layer decreases essentially nonlinearly, we may conclude that the liquid economy decreases. Consequently, it may be concluded that it is inexpedient to form rather thick water films for quenching the thermal decomposition reaction of the FCM (an increase in the thickness of these films leads to a decrease in both the times τ_d and the water economy).

CONCLUSIONS

1) It has been established that the integral parameter H_w characterizing the distance between water drops strongly influences the quenching times of the reaction of thermal decomposition of the typical FCMs. It has also been shown that depending on the temperature of the vapor-gas mixture near the FCM surface and, as a consequence, between liquid drops, the times τ_d may differ by 10–40% at identical values of H_w .

2) It has been found that variations in the temperature of the vapor-gas mixture over the range corresponding to the typical wake of the "water slug" ($\Theta_f = 0.3$ – 0.45) leave the times τ_d practically unaltered (deviations are less than 1%). This

result shows that to quench the reaction of thermal decomposition of the FCM, it is enough to form over its surface a vapor-gas mixture with a temperature $\Theta_f = 0.3\text{--}0.45$ by finely spraying [7–16] water in the flame combustion zone. It should be noted that the presence of liquid drops or liquid films of large thicknesses (the more so of thicknesses much larger than L_f) on the surface of the thermally decomposing FCM seems inexpedient.

3) It has also been established that during the times τ_d obtained as a result of the computational modeling, the thicknesses of evaporating layers of water drops amount to 15% of the characteristic size L_{dr} . In the case of a monolithic film (at $H_w = 0$), this value does not exceed 1%. The revealed effect shows that the economy of the liquid in quenching the reaction of thermal decomposition of FCMs decreases considerably when large quantities of water are supplied.

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NOTATION

C , specific heat capacity, J/(kg·K); C_f , dimensionless concentration of gaseous thermal decomposition products of the FCM; C_v , dimensionless concentration of water vapors; D , diffusion coefficient, m^2/s ; G_p , dimensionless parameter; Fo , Fourier number; h, l , sizes of the solution domain, m; h_{dr}, l_{dr} , sizes of water drops, m; H, L, H_{dr}, L_{dr} , dimensionless analogs of h, l, h_{dr}, l_{dr} ; H_w , dimensionless distance between drops; E , activation energy of the thermal decomposition reaction, J/mole; k^0 , preexponent of the thermal decomposition reaction, s^{-1} ; k_β , dimensionless parameter of liquid evaporation; l_m , coordinate scale, m; L_f , dimensionless thickness of the FCM; M , molar mass, kg/kmole; P , pressure of water vapors near the evaporation boundary, N/m²; P^n , pressure of saturated water vapors, N/m²; Q_2 , thermal evaporation effect, J/kg; Q_3 , thermal effect of thermal decomposition, J/kg; R , universal gas constant, J/(mole·K); S_r , dimensionless parameter; T , temperature, K; T_m , temperature scale, K; T_w , initial temperature of water, K; T_{2s} , temperature at the liquid evaporation boundary, K; ΔT , temperature difference, K; t_m , time scale, s; W_2 , mass evaporation rate, kg/(m³·s); W_3 , mass thermal decomposition rate, kg/(m³·s); W_3^Σ , mass rate of injection of thermal decomposition products into the gas phase, kg/(m³·s); x, y , Cartesian coordinates; X, Y , dimensionless analogs of x and y ; β , dimensionless evaporation coefficient; λ , heat conductivity, W/(m·K); ρ , density, kg/m³; τ , dimensionless time; τ_d , dimensionless time of completion of the thermal decomposition reaction; φ , fraction of the thermally decomposable substance; Θ , dimensionless temperature; Θ_d , dimensionless temperature of thermal decomposition; Θ_f , dimensionless temperature of the vapor-gas mixture. Subscripts: 0, initial state; 1, vapor-gas mixture; 2, water; 3, FCM; 11, water vapor; 12, gaseous thermal decomposition products; 31, solid pyrolysis products of the material; 32, gaseous FCM pyrolysis products; d, thermal decomposition; dr, drop; f, mixture of gaseous thermal decomposition products and water vapor; m, scale; v, vapor; w, water.

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