Journal of Engineering Physics and Thermophysics, Vol. 74, No. 4, 2001

PROBLEM OF DRYING OF A LAYER OF COMBUSTIBLE FOREST MATERIALS

A. M. Grishin, A. N. Golovanov,
L. Yu. Kataeva, and E. L. Loboda

UDC 536.24

Physical and mathematical modeling of drying of a layer of combustible forest materials (CFMs) is considered in a conjugate formulation within the framework of which the equations of a binary boundary layer and the equations of heat and mass transfer in a layer of combustible forest materials are solved. Boundary conditions for the laws of conservation of mass and energy are written on the interface of media. It is found experimentally and theoretically that the velocities of the flow and radiation strongly affect the time of drying of a layer of combustible forest materials, whereas the effect of the angle of inclination (slope) between the underlying surface and the horizontal plane is insignificant.

It is known that fires annually cause great damage to forests all over the world. Therefore, solution of the problem of reliable prediction of a forest-fire hazard is topical. The techniques of its prediction have virtually not been developed at present. For example, in Russia, the V. G. Nesterov index of combustibility is used to evaluate a fire hazard [1], although this index does not allow for the effect of wind velocity, solar radiation, and the type of ground and combustible forest materials on their drying [2]. Recently, attempts have been made to refine the technique of prediction of a fire hazard [3–6], but, unfortunately, they all have the same drawbacks as the V. G. Nesterov combustibility index [7, 8].

In the present work, we give new general physical and mathematical models of drying of the layer of combustible forest materials. In the calculations, use was made of the refined kinetics of drying of combustible forest materials that is obtained on the basis of experimental data on drying of needles of pine and other coniferous species of trees. Calculation results are compared with the data of experiments on convective drying of combustible forest materials using a subsonic wind tunnel.

Physical Formulation of the Problem. We have a layer of combustible forest materials (fallen twigs, needles, and dry grass) which is blown around by wind and heated by solar radiation. The height of the layer h, wind velocity u_e at a height of 2 m, fractional composition of the layer of combustible forest materials, and thermophysical coefficients which characterize transport processes and evaporation of water from combustible forest materials are known. It is necessary to determine the period of drying of the layer of combustible forest materials, with certain weather conditions being specified, i.e., to find a period during which the moisture content of combustible forest materials will become lower than critical. The x axis is directed windward along the soil–layer of combustible forest materials interface, while the z axis is perpendicular to the y axis; $z = 0$ corresponds to the soil–layer of combustible materials interface and $x = 0$ — to the left boundary of the layer of combustible forest materials.

For simplicity of analysis, we will use the following assumptions:

(1) all parameters are independent of the coordinate y (the plane problem is considered);

Tomsk State University, Tomsk, Russia; email: fire@fire.tsu.tomsk.su. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 74, No. 4, pp. 58–64, July–August, 2001. Original article submitted September 11, 2000; revision submitted February 9, 2001.

(2) the medium of combustible forest materials consists of a dry organic substance (volumetric fraction φ_1), water in a substance-bound state (volumetric fraction φ_2), free water (volumetric fraction φ_3), and air (volumetric fraction φ_4), i.e., water vapor and the other components;

(3) inclusions in the gas phase — elements of the soil cover — have the same characteristic dimension and specific surface and are capillary-porous colloid bodies;

(4) the layer of combustible forest materials involves inclusions in the form of rain drops (in the case of rainy weather) and water vapor; until the moment of ultimate moisture content φ_3^* is reached, rain drops are absorbed by the elements of combustible forest materials and then, when $\varphi_3 > \varphi_3^*$, they precipitate onto the soil with a velocity w_3;

(5) the mode of flow in the boundary layer above a rough underlying surface can be laminar, transient, or turbulent;

(6) the mode of flow above a rough underlying surface is steady-state and, in the general case, the flow velocity follows a logarithmic dependence on height;

(7) the gas phase is an effective binary mixture consisting of water vapor and dry air;

(8) filtration of moisture from the soil to the upper boundary of the layer caused by the effect of capillary forces is observed in the soil cover.

These assumptions are the essence of a physical model of drying of the layer of combustible forest materials. It is expedient to model the effect of atmospheric precipitation by assigning new initial conditions for the volumetric fractions of the phases. In other words, within the framework of this model we do not calculate the parameters of state of the medium in the layer of combustible forest materials during the rain, and the moisture content and temperature in the layer of combustible forest materials after the rain are specified on the basis of meteorological data.

System of Boundary-Layer Equations. Following [7], we write the basic system of equations of a near-ground boundary layer in the system of coordinates x, z:

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho w}{\partial z} = 0\,, \tag{1}$$

$$\rho \left(u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} \right) + \frac{\partial}{\partial z} \left(\mu_{\text{ef}} \frac{\partial u}{\partial z} \right) = \frac{\partial P_{\text{e}}}{\partial x} - \rho g \sin \alpha\,, \tag{2}$$

$$\frac{\partial P_{\text{e}}}{\partial z} = - \rho g \cos \alpha\,, \tag{3}$$

$$P_{\text{e}} = \frac{\rho R T}{M}\,, \quad \frac{1}{M} = \frac{C_1}{M_1} + \frac{C_2}{M_2}\,, \tag{4}$$

$$\rho \left(u \frac{\partial C_2}{\partial x} + w \frac{\partial C_2}{\partial z} \right) = \frac{\partial}{\partial z} \left(\rho D_{\text{ef}} \frac{\partial C_2}{\partial z} \right) - R_2^{(\text{s})}\,, \tag{5}$$

$$\rho C_p \left(u \frac{\partial T}{\partial x} + w \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial z} \left(\lambda_{\text{ef}} \frac{\partial T}{\partial z} \right) + K \left(u \frac{\partial P_{\text{e}}}{\partial x} + w \frac{\partial P_{\text{e}}}{\partial z} \right) + q_2 R_2^{(\text{s})}\,. \tag{6}$$

In what follows, in solution of specific problems, we assume the quantity $R_2^{(s)}$, which characterizes the rate of condensation of water vapor, to be equal to zero.

System of Heat- and Mass-Transfer Equations for the Layer of Combustible Forest Materials. To formulate a conjugate problem we must write, along with the boundary-layer equations, the equations which express the laws of conservation of mass and momentum for the layer of combustible forest materials. It is known that the length of the layer is much greater than its height; therefore, the assumption that

$$\frac{\partial T}{\partial z} >> \frac{\partial T}{\partial x}, \quad \frac{\partial C_1}{\partial z} >> \frac{\partial C_1}{\partial x} \text{ and e. g.} \tag{7}$$

is quite justified.

With account for these assumptions, we have the following system for mathematical description of drying of the layer of combustible forest materials:

$$\frac{\partial (\rho_4 \varphi_4)}{\partial t} + \frac{\partial (\rho_4 \varphi_4 w)}{\partial z} = Q , \tag{8}$$

$$\left(\frac{\partial (\rho_4 \varphi_4 C_p T)}{\partial t} + \frac{\partial (\rho_4 \varphi_4 C_p w T)}{\partial z}\right) = \frac{\partial}{\partial z}\left(\lambda_{\text{ef}} \frac{\partial T}{\partial z}\right) + \alpha_v (T_{\text{s}} - T) + Q C_p T , \tag{9}$$

$$\frac{\partial (\rho_1 \varphi_1)_i}{\partial t} = 0 , \quad R_{2i} = \frac{k_{2i}\, \rho_2 \varphi_2}{\sqrt{T}} \left[P_{02} \exp\left(-\frac{E_i}{RT}\right) - P_2\right], \quad i = 1, \ldots , N ; \tag{10}$$

$$\frac{\partial (\rho_2 \varphi_2)_i}{\partial t} + \frac{\partial (\rho_2 \varphi_2 w_2)_i}{\partial z} = R_{3i} - R_{2i} , \quad i = 1, \ldots , N ; \tag{11}$$

$$\left(\sum_{i=1}^{3} \rho_i\, \varphi_i C_{pi}\right) \frac{\partial T_{\text{s}}}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{\text{s}} \frac{\partial T_{\text{s}}}{\partial z}\right) + \frac{\partial q_{\text{r.s}}}{\partial z} - q_2 (R_2 + R_3) - \alpha_v (T_{\text{s}} - T) ; \tag{12}$$

$$-\frac{\partial}{\partial z}\left(\frac{c}{3k_{\text{s}}} \frac{\partial U_{\text{r}}}{\partial z}\right) + k_{\text{s}} (c U_{\text{r}} - 4\sigma T_{\text{s}}^4) = 0 , \quad q_{\text{r.s}} = -\frac{c}{3k_{\Sigma}} \frac{\partial U_{\text{r}}}{\partial z} ; \tag{13}$$

$$\frac{\partial (\rho_3 \varphi_3)_i}{\partial t} + \frac{\partial (\rho_2 \varphi_3 w_3)_i}{\partial z} = - R_{3i} - R_{32}^{(i)} , \quad i = 1, \ldots , N ; \tag{14}$$

$$\left(\frac{\partial (\rho_4 \varphi_4 C_2)}{\partial t} + \frac{\partial (\rho_4 \varphi_4 w C_2)}{\partial z}\right) = \frac{\partial}{\partial z}\left(\rho_4\, \varphi_4 D_{\text{s}} \frac{\partial C_2}{\partial z}\right) + (R_2 + R_3) ,$$

$$R_2 = \sum_{i=1}^{N} R_{2i} , \quad R_3 = \sum_{i=1}^{N} R_{3i} , \quad R_{3i} = \frac{k_{3i} (\rho_3 \varphi_3)_i}{\sqrt{T}} \left[P_{03} \exp\left(-\frac{L_i}{RT}\right) - P_2\right] ; \tag{15}$$

$$P_e = \frac{\rho_4 RT}{M}, \quad \frac{1}{M} = \frac{C_1}{M_1} + \frac{C_2}{M_2}, \quad C_1 + C_2 = 1 . \tag{16}$$

In writing the energy equation in the *k*th phase, we assumed that transfer of energy by radiation in the layer of combustible forest materials is negligibly small compared to convective heat transfer.

In what follows, for the sake of definiteness, we assume that $N = 1$, i.e., the layer of combustible forest materials consists of one fraction with effective properties corresponding to the properties of a real layer of combustible forest materials.

Boundary and Initial Conditions for the Basic System of Equations. The system of equations (1)–(6) must be solved with account for the following boundary and initial conditions:

$$u\big|_{z=h+0} = 0, \quad T\big|_{z=h+0} = T\big|_{z=h-0}, \quad C_2\big|_{z=h+0} = C_2\big|_{z=h-0}; \tag{17}$$

$$u\big|_{z=\delta} = u_e, \quad T\big|_{z=\delta_1} = T_e, \quad C_2\big|_{z=\delta_2} = C_{2e}; \tag{18}$$

$$x = 0: \quad T = T_\infty, \quad u = u_\infty, \quad w = 0, \quad C_2 = C_{2e} . \tag{19}$$

To determine u_e, T_e, and P_e, we must solve equations of gas dynamics with the corresponding boundary conditions. In the general case, these equations cannot be solved analytically. However, at $K = 0$ for an isothermal flow and $K = 1$ for an isentropic flow beyond the boundary layer, we are able to obtain integrals of these equations analytically [7]:

$$\frac{u_e^2}{2} + \int \frac{dP_e}{P_e} + g\left(\delta \cos\alpha + \int_0^x \sin\alpha \, dx\right) = A_{1e}; \tag{20}$$

$$T_e = \text{const}, \quad P_e / P_e^{\gamma} = A_{2e}, \quad \gamma = C_p / C_v . \tag{21}$$

To determine the thickness of the boundary layer, we adopt the conditions

$$\left.\frac{\partial u}{\partial z}\right|_{z=\delta} = m_1, \quad \left.\frac{\partial T}{\partial z}\right|_{z=\delta_1} = m_2, \quad \left.\frac{\partial C_2}{\partial z}\right|_{z=\delta_2} = 0, \tag{22}$$

which are the generalization of the known conditions of M. E. Shvets [9]; in the general case, m_1 and m_2 are functions of x which characterize the vorticity of flow and the temperature gradient for $z = \delta$ and $z = \delta_1$. If the external flow is isothermal, then $m_2 = 0$, and for adiabatic flows $m_2 = g/C_p$.

We will consider the soil temperature and the coefficients of heat exchange between the soil and the air and the elements of combustible forest materials to be known from measurements [10]. Then for the gas in the macropores of the layer of combustible forest materials and for the dry organic substance above the soil we have boundary conditions of the first or second kind:

$$T\big|_{z=0} = T_0, \quad T_s\big|_{z=0} = T_0, \quad \lambda_s \left.\frac{\partial T_s}{\partial z}\right|_{z=0} = \alpha_0 (T_s - T_0)\big|_{z=0}, \quad \lambda \left.\frac{\partial T}{\partial z}\right|_{z=0} = \alpha_0 (T - T_0)\big|_{z=0} . \tag{23}$$

Boundary conditions for the radiation density have the form [6, 9]

$$-\frac{c}{3k_\Sigma}\frac{\partial U_r}{\partial z}\bigg|_{z=0} = 0\,, \quad -\frac{c}{3k_\Sigma}\frac{\partial U_r}{\partial z}\bigg|_{z=h} = [(1-A)\, q_r\,(h) \cos\alpha - \varepsilon_s \sigma T_s^4 \varphi_s - \varepsilon\sigma T_w^4 \varphi_w + J_a \cos\alpha]\,. \tag{24}$$

The condition of energy balance for the gas phase and the equality of temperatures on the upper boundary of the layer of combustible forest materials have the form [7]

$$(1-\varphi_s)\,\lambda \frac{\partial T}{\partial z}\bigg|_{z=h+0} = (1-\varphi_s)\,\lambda \frac{\partial T}{\partial z}\bigg|_{z=h-0}\,, \quad T\big|_{z=h+0} = T\big|_{z=h-0}\,. \tag{25}$$

From the condition of thermal-energy balance on the boundary "gas–condensed phase" we obtain [7]

$$\varphi_s\,\lambda \frac{\partial T}{\partial z}\bigg|_{z=h+0} = \varphi_s\,\lambda_s \frac{\partial T_s}{\partial z}\bigg|_{z=h-0} + (\varphi_s q_2 R_2)_w - \varphi_s q_r\big|_{z=h-0}\,. \tag{26}$$

We write the balance of the water-vapor mass on the upper boundary of the layer of combustible forest materials and the equality of concentrations in the following form [7]:

$$\rho D_{ef}\frac{\partial C_2}{\partial z}\bigg|_{z=h+0} + (\rho w C_2)\big|_{z=h+0} = \left(\rho_4\varphi_4 D_s \frac{\partial C_2}{\partial z}\right)\bigg|_{z=h-0} + (\rho_4\varphi_4 w C_2)\big|_{z=h-0}\,,$$

$$C_2\big|_{z=h-0} = C_2\big|_{z=h+0}\,. \tag{27}$$

The law of conservation of mass of the gas phase on the interface has the form [7]

$$(\rho w)_{z=h+0} = \varphi_s R_2 + (\rho_4\,\varphi_4 w)_{z=h-0}\,. \tag{28}$$

With account for (26), we represent the boundary conditions (25) as

$$\rho D_{ef}\frac{\partial C_2}{\partial z}\bigg|_{z=h+0} + \varphi_s R_2 C_2\big|_{z=h} = \left(\rho_4\varphi_4 D_s \frac{\partial C_2}{\partial z}\right)\bigg|_{z=h-0}\,, \quad \rho_4\varphi_4 D_s \frac{\partial C_2}{\partial z} = 0\,. \tag{29}$$

The initial conditions for the considered problem have the form

$$T\big|_{t=0} = T_{in}\,, \quad T_s\big|_{t=0} = T_{sin}\,, \quad C_2\big|_{t=0} = C_{2in}\,, \quad w\big|_{t=0} = 0\,, \quad \varphi_i\big|_{t=0} = \varphi_{iin}\,. \tag{30}$$

Technique and Results of Experiments. To check the reliability of the results of calculations according to the model of drying of combustible forest materials we conducted a number of experiments.

Specimens of an unusual porous medium which includes the elements of combustible forest materials (needles of pine, spruce, and cedar) and the air were the object of investigation. The elements of combustible forest materials located on a horizontal surface were streamlined by a laminar air flow generated by a subsonic wind tunnel of the MT-324 type. The longitudinal and transverse dimensions of the studied specimen of the layer of combustible forest materials were 0.1 × 0.1 m and the height was h = 0.02 m. The boundary-layer thickness was measured using a thermoanemometer. The packaging density of combustible forest materials with chaotic orientation of the needles was varied: ρ_s = (44.5–110.6) kg/m^3. The angle of inclination of the plane with the elements of combustible forest materials and the vector of the air-flow velocity α = (0–20)^o was changed using a special traverse gear, while the velocity of the air flow u_e = (0–0.695) m/sec was determined by a Pitot–Prandtl tube (mouthpiece), an MMN-240 micromanometer, and a ther-

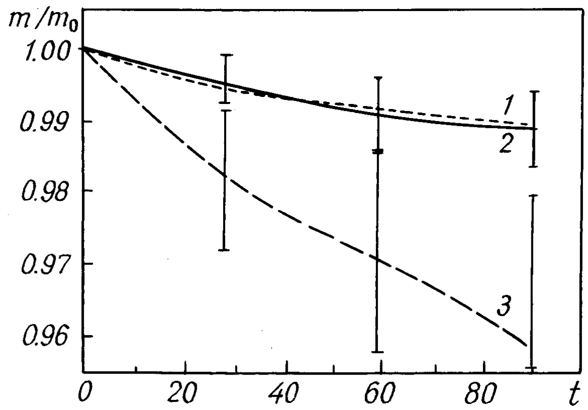

Fig. 1. Experimental data of the loss of mass of pine needles and confidence intervals with different packaging densities: 1) ρ_s = 110.6 kg/m^3, W_s = 0.0526, P_e = 755 mm Hg, φ = 76%, and T_{in} = 291 K; 2) ρ_s = 55.3 kg/m^3, W_s = 0.0526, P_e = 757 mm Hg, φ = 72%, and T_{in} = 291 K; 3) ρ_s = 44.5 kg/m^3, W_s = 0.413, P_e = 754 mm Hg, φ = 32%, and T_{in} = 300 K. t, min.

moanemometer. As the measurements showed, there was a laminar mode of flow past the layer of combustible forest materials. The moisture content of combustible forest materials was determined from the formula $W_s = (m - m_0)/m_0$, where m and m_0 are the values of the mass and the absolutely dry mass of combustible forest materials, which are obtained by weighing dry and wet specimens on a second class ADV-200M-type analytical balance with an accuracy of 10^{-4} g. The quantity W_s and the air temperature varied within W_s = (0.0539–0.7036) and T_{in} = (291–302) K. Atmospheric pressure was measured using a BAMM-1 aneroid barometer and varied within P_e = (748–764) mm Hg, while the relative humidity of the air changed within φ = (32–77)% and was determined using an MV-4M aspiration psychrometer. The varied mass of the specimens m/m_0, which decreased with time as a result of the drying, was determined. The time of drying t varied within 90–300 min. The total relative errors of determination of the parameters did not exceed $\delta V_e/V_e \cdot 100\% \le 4.2\%$, $\delta m/m \cdot 100\% \le 2.1\%$, $\delta T_{in}/T_{in} \cdot 100\% \le 5.3\%$, $\delta P_e/P_e \cdot 100\% \le 6.0$, and $\delta\varphi/\varphi \cdot 100\% \le 7.9\%$. The confidence intervals were calculated from the results of 3–5 measurements with a confidence level of 0.95 [11].

In deciding on conditions of air flow past the specimens of combustible forest materials, the meteorological parameters of the atmosphere and the packaging density of combustible forest materials were selected in such a way as to correspond to their natural values.

Figure 1 presents typical dependences of the loss of mass of pine needles on the time with different packaging densities. The pressure was measured in mm Hg. Curves 1 and 2 were obtained for the same moisture content of the elements of combustible forest materials and the same parameters of the environment. These curves virtually coincide, and their confidence intervals intersect at all points of measurements. Curve 3 reflects a significantly different initial moisture content and a higher temperature of the air. In this case, the confidence intervals of curves 1, 2, and 3 intersect everywhere except the last point. We can draw the conclusion that within the indicated range of measurements the packaging density obtained in a natural way is an insignificant factor, and a stronger effect on the drying of combustible forest materials is exerted by the initial moisture content of combustible forest materials, the temperature of the environment, and the relative humidity of the air.

Results of Numerical Solution of the Problem and Their Comparison with Experimental Data. In the calculations, it was assumed that a boundary layer of air appears above the layer of combustible forest materials, and the conjugate problem of heat and mass exchange between the air flow and the layer of combustible forest materials was solved. In this case, use was made of the following numerical values of the

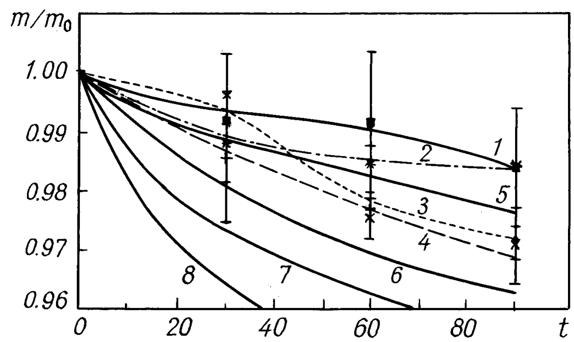

Fig. 2. Experimental (1–4) and theoretical (5–8) data on the loss of mass of pine needles for different angles of inclination of the plane (ρ_s = 55.3 kg/m^3): 1) W_s = 0.413, P_e = 751 mm Hg, φ = 32%, T_{in} = 302 K, α = 0^o, and V_e = 0 m/sec; 2) W_s = 0.3417, P_e = 756 mm Hg, φ = 28%, T_{in} = 302 K, α = 20^o, and V_e = 0.613 m/sec; 3) W_s = 0.1733, P_e = 757 mm Hg, φ = 29%, T_{in} = 300 K, α = 10^o, and V_e = 0.613 m/sec; 4) W_s = 0.413, P_e = 754 mm Hg, φ = 32%, T_{in} = 302 K, α = 0^o, and V_e = 0.613 m/sec; 5) W_s = 0.413, P_e = 754 mm Hg, φ = 32%, T_{in} = 302 K, α = 0^o, and V_e = 0.613 m/sec (solar radiation is absent); 6) W_s = 0.413, P_e = 754 mm Hg, φ = 32%, T_{in} = 302 K, α = 0^o, and V_e = 0.613 m/sec (solar radiation is absent); 7) W_s = 0.413, P_e = 754 mm Hg, φ = 32%, T_{in} = 302 K, α = 20^o, and V_e = 0.613 m/sec (solar radiation is taken into account); 8) W_s = 0.413, P_e = 754 mm Hg, φ = 32%, T_{in} = 302 K, α = 0^o, and V_e = 0.613 m/sec (solar radiation is taken into account).

parameters which determine the solution of the problem: density of a dry organic substance ρ_1 = 300 kg/m^3, water density ρ_2 = 1000 kg/m^3, atmospheric pressure $P_e = 1.01 \cdot 10^5$ Pa, specific energy of evaporation L = 40,500 J/mole, albedo A = 0.12, thickness of the layer of combustible forest materials h = 0.03 m, heat capacity at constant pressure for water in a substance-bound state $C_{p3} = 4.18 \cdot 10^6$ J/kg, density of the solar-radiation flux q_r = 175 J/(m^2·sec), emissivity of combustible forest materials ε_s = 0.7, emissivity of air ε = 0, Stefan–Boltzmann constant $\sigma = 5.67 \cdot 10^{-8}$ W/(m^2·K^4), density of longwave radiation from the atmosphere J_a = 281.91 J/(m^2·sec), pre-exponential factor P_0 = 2329.6 Pa, specific heat capacity of the layer of combustible forest materials C_p = 1010 J/kg, heat of evaporation of water q_2 = 2250 kJ/kg, specific heat capacity of water bound to a dry combustible forest material $C_{p2} = 4.18 \cdot 10^6$ J/(kg·K), $R_2^{(s)} = 0$, mass concentration of water vapor in the atmosphere C_{2e} = 0.0113, molar mass of air M_1 = 30, molar mass of water M_2 = 18, and kinematic viscosity of air $\nu = 1.84 \cdot 10^{-5}$ N·sec/m^2. It was assumed that $w_2 = 0$, $w_3 = 0$, and $R_{3i} = 0$.

It follows from the formulation of the problem that the effect of the angle of inclination α of the underlying surface to the horizontal plane on the drying of combustible forest materials can manifest itself via a change in the velocity of the external flow u_e [12] or via a change in cos α in (3) and (24). In this paper, solar radiation was not modeled in laboratory experiments. Therefore, the main effect on the process of drying of combustible forest materials was exerted by the air-flow temperature, while the effect of the angle α, as follows from the analysis of experimental data with $0 < \alpha < 20^o$, is insignificant (see Fig. 2 and Tables 1 and 2).

Tables 1 and 2 give results of the calculations for different values of the angles α and the packaging density of the layer of combustible forest materials ρ. A change from 0 to 20^o in the angle α virtually does not have the same effect on the drying of combustible forest materials as the change in the packaging density of combustible forest materials within the limits corresponding to real conditions does.

TABLE 1. Results of Calculating the Loss of Mass of Pine Needles as a Function of the Angle of Inclination of the Earth's Surface in the Absence of Solar Radiation

t, min	m/m_0		
	$\alpha = 0^o$	$\alpha = 10^o$	$\alpha = 20^o$
1	0.999940	0.999940	0.999940
10	0.999399	0.999401	0.999402
20	0.998800	0.998803	0.998804
30	0.998202	0.998206	0.998209
40	0.997606	0.997611	0.997615
50	0.997011	0.997018	0.997022
60	0.996417	0.996426	0.996431
70	0.995825	0.995835	0.995841
80	0.995234	0.995246	0.995252
90	0.994645	0.994658	0.994665

TABLE 2. Results of Calculating the Loss of Mass of Pine Needles as a Function of the Packaging Density of the Elements of Combustible Forest Materials

t, min	m/m_0	
	$\rho_s = 44.5$ kg/m^3	$\rho_s = 110.6$ kg/m^3
1	0.999759	0.999759
10	0.997597	0.997597
20	0.995200	0.995200
30	0.992808	0.992808
40	0.990422	0.990422
50	0.988042	0.988042
60	0.985668	0.985668
70	0.983299	0.983299
80	0.980936	0.980936
90	0.978579	0.978579

Figure 2 shows the dependences of the loss of mass of pine needles on the time for different angles of inclination α obtained as a result of numerical solution of the problem and laboratory experiments. It is obvious that the confidence intervals for all experimental curves intersect at all points, and we can draw the conclusion that the effect of the angle of inclination of the plane is insignificant. In theoretical studies, by solution of the conjugate problem we modeled the process of drying of combustible forest materials which is maximum in similarity to real conditions, or more precisely, we allowed for solar radiation and its change with variation of the angle of inclination of the earth's surface. Curve 5 corresponds to the process of drying of the horizontal surface in the absence of solar radiation for a wind velocity of 0.2 m/sec, curve 6 corresponds to the process of drying of the horizontal surface in the absence of solar radiation for a wind velocity of 0.613 m/sec, curve 7 reflects the process of drying of combustible forest materials for an angle of inclination of 20^o and with account for solar radiation, and curve 8 — the process of drying of combustible forest materials for an angle of inclination of 0^o and with account for solar radiation. Analyzing curves 5–8, we can draw the conclusion that solar radiation strongly affects the process of drying of combustible forest materials; the angle of inclination of the earth's surface also affects the rate of drying. As the results of theoretical investigations showed, a strong effect on the time of drying and the shape of drying curves is exerted by the density of solar radiation, the initial moisture content of combustible forest materials, the air temperature, the relative humidity of the air, and atmospheric pressure, which were different for all curves.

Comparing the experimental curves with the results of the numerical experiment (see Fig. 2), we can note that numerical curve 5 falls completely within the confidence intervals for the corresponding experimental curve 1, and curve 6 at the initial stage of drying falls completely within the confidence intervals of the corresponding experimental curve 4. Proceeding from the above, we can draw the conclusion that the mathematical model describes the process of drying of combustible forest materials adequately within the framework of the above assumptions.

NOTATION

h, height of the layer of combustible forest materials; u_e, wind velocity on the outer edge of the boundary layer; w_3, velocity of precipitation of rain droplets onto the soil; ρ, density of moist air; u and w, projections of the air velocity on the x and z axes; $\mu_{ef} = \mu + \mu_t$, effective value of the coefficient of dynamic viscosity of the air; μ, coefficient of molecular dynamic viscosity of the air; μ_t, coefficient of turbulent dynamic viscosity of the air; P_e, pressure on the outer edge of the boundary layer; g, acceleration of gravity; α, angle of inclination between the tangential plane to the underlying surface and the horizontal plane; R, universal gas constant; T, absolute temperature; M, molecular mass of the gas mixture; C_1, mass concentration of all components of dry air; C_2, mass concentration of the water vapor in the air; M_1, molar mass of dry air; M_2, molar mass of the water vapor; $D_{ef} = D + D_t$, effective value of the coefficient of diffusion; D, molecular coefficient of diffusion for the air above the layer of combustible forest materials; D_t, coefficients of turbulent diffusion in the dry air–water vapor mixture; $R_2^{(s)}$, mass rate of condensation of the water vapor; $\lambda_{ef} = \lambda + \lambda_t$, effective value of the coefficient of thermal conductivity; λ, coefficient of molecular thermal conductivity of the air; λ_t, coefficient of turbulent thermal conductivity; $K = 0$ or 1, for isobaric and isentropic flows, respectively; q_2, thermal effect of condensation of the water vapor; t, time; $Q = (R_2 + R_3)$, total rate of evaporation of bound and free water; R_2, mass rate of evaporation of bound water; R_3, mass rate of evaporation of droplets of free water which stuck to the elements of combustible forest materials; $C_p = C_{p1}C_1 + C_{p2}C_2$, heat capacity of the gas phase (moist air) at constant pressure; C_{p1} and C_{p2}, heat capacity of the dry air and the water vapor, respectively, at constant pressure; $\alpha_v = \alpha_s s$, coefficient of volumetric convective heat exchange between the elements of combustible forest materials and the air; α_s, coefficient of surface convective heat exchange between an individual element of combustible forest materials and the air; s, specific area of the layer of combustible forest materials; T_s, temperature of the condensed phase (dry organic substance + free and bound water); N, number of fractions of combustible forest materials; R_{2i}, mass rate of evaporation of bound water for the ith fraction of combustible forest materials; R_{3i}, mass rate of evaporation of free water for the ith fraction of combustible forest materials; k_{2i}, pre-exponent of the process of evaporation of bound water in the ith fraction of combustible forest materials; ρ_1, intrinsic density of the dry organic substance; ρ_2, intrinsic density of water bound to the dry substance; P_{02}, pre-exponential factor in the law of evaporation of bound water; E_i, molar heat of evaporation of bound water for the ith fraction of combustible forest materials; P_2, partial pressure of the water vapor in the layer of combustible forest materials; w_2, velocity of motion (filtration) of bound water in the layer of combustible forest materials; C_{p3}, heat capacity of free water in the layer of combustible forest materials at constant pressure; ρ_3, intrinsic density of free water; $q_{r.s}$, density of radiative heat flux in the layer of combustible forest materials; c, velocity of light; k_s, integral coefficient of absorption of the radiation in the layer of combustible forest materials; U_r, density of radiation averaged over all frequencies; σ, Stefan–Boltzmann constant; k_Σ, integral coefficient of attenuation of radiation; R_{3i}, mass rate of evaporation of the droplets of free water for the ith fraction of combustible forest materials; $D_s = \varphi_4 D$, coefficient of molecular diffusion of the water vapor; k_{3i}, pre-exponent in the law of drying of the free component of the ith fraction of combustible forest materials; P_{03}, pre-exponential factor in the law of evaporation for free water; L_i, molar heat of evaporation of free water for the ith fraction of combustible forest materials; δ, thickness of the dynamic boundary layer; δ_1, thickness of the thermal boundary layer; δ_2, thickness of the concentration boundary layer; A_{1e} and A_{2e}, constants which, in the general case, change on transition from one streamline to another; γ, adiabatic index; C_v, heat capacity at constant volume; m_1, function characterizing the vorticity of flow; m_2, function characterizing the temperature gradient; T_0, soil temperature; λ_s, coefficient of thermal conductivity of the condensed phase of the layer of combustible forest materials; α_0, coefficient of heat exchange between the layer of combustible forest materials and the soil; A, albedo of the layer (fraction of the incident radiation flux reflected to the environment); $q_r(h) = q_{r1} + q_{r2}$, density of the solar-radiation flux on the upper boundary of the layer of combustible forest materials; q_{r1} and q_{r2}, shortwave densities of the fluxes of direct and scattered solar radiation; ε_s, emissivity of the layer of combustible forest materials and the air; $\varphi_s = \varphi_1 + \varphi_2 + \varphi_3$, volumetric fraction of the condensed phase in the layer of combustible forest materials which is equal to zero when $z \geq h + 0$; ε, emissivity of the gas phase; J_a, density of the longwave-radiation flux from the atmosphere which is caused by the presence of dust, water vapor, and polyatomic gases in the atmosphere; $(-\varepsilon_s \sigma T_s^4 \varphi_s)$, density of the longwave-radiation flux from the combustible forest materials on the underlying surface to the atmosphere; $\rho_4\varphi_4$, density of the gas phase in the layer of the soil cover; ρ_4, intrinsic density of the gas phase, respectively; u_e, velocity of the air flow on the outer boundary of the layer of combustible forest materials. Sub- and superscripts: i, corresponds to the fraction number; *, corresponds to the state of moisture saturation; ∞ and e, parameters of the undisturbed flow and the outer edge of the boundary layer; w, refers to the values for $z = h$; in, initial instant of time; s, corresponds to the parameters of state and the characteristics of the condensed phase.

REFERENCES

1. V. G. Nesterov, *Combustibility of Forest and Methods of Its Determination* [in Russian], Moscow–Leningrad (1949).
2. A. V. Luikov, *Theory of Drying* [in Russian], Moscow (1968).
3. G. N. Korovin, V. D. Pokryvailo, Z. M. Grishman, et al., in: *Forest Fires and Fighting Them* [in Russian], Leningrad (1986), pp. 18–31.
4. É. N. Valendik, E. K. Kisilyakhov, and V. N. Ambarnikov, in: *Ext. Abstr. of Papers Presented to All-Union Conf. "Aerospace Methods of Investigation of Forests,"* Krasnoyarsk, July 7–9, 1984 [in Russian], Krasnoyarsk (1984), pp. 120–121.
5. A. I. Sukhinin and E. Ponomarev, *Estimation of the Moisture Content of Combustible Forest Materials by the Radiation Temperature*. Dep. at VINITI 15.04.98, No. 1144-V98.
6. E. Ponomarev and A. I. Sukhinin, *Spatial Estimate of a Fire Hazard in a Forest by Weather Conditions*. Dep. at VINITI 14.05.97, No. 1620-V97.
7. A. M. Grishin, *Mathematical Modeling of Forest Fires and New Methods of Fighting Them*, Tomsk (1997).
8. A. M. Grishin, *Physics of Forest Fires* [in Russian], Tomsk (1994).
9. M. E. Shvets, *Prikl. Mat. Mekh.*, **14**, Issue 1, 30–43 (1950).
10. A. F. Chudnovskii, *Thermal Physics of Soils* [in Russian], Moscow (1972).
11. H. Schenck, Jr., *Theories of Engineering Experimentation* [Russian translation], Moscow (1972).
12. P. N. Romanenko, *Hydrodynamics and Heat Transfer in a Boundary Layer*, *Handbook* [in Russian], Moscow (1974).