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DETERMINATION OF THE CHARACTERISTICS OF MASS TRANSFER IN CERTAIN COMBUSTIBLE FOREST MATERIALS

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The main characteristics of moisture transfer (the coefficients of moisture capacity and moisture conductivity) for the most widespread elements of combustible forest materials (CFMs), namely, needles of pine, cedar, and spruce, are found experimentally according to the procedure of A. V. Luikov, which is based on the introduction of a scale of moisture-transfer potential. The data obtained are compared with the results of other authors. Analysis of the structure of the CFM elements made it possible to establish that complex processes (desorption, adsorption, and osmosis) associated with a change in the fine structure of the needles during their drying occur inside the CFM elements.

Formulation of the Problem and Object of Investigation. For space monitoring of forests, the spectral coefficients of brightness are used; these coefficients make it is possible to describe and recognize types of wood, evaluate their physiological state, and predict a forest-fire hazard. Moreover, from the spectral density of intrinsic radiation of the site of a forest fire one is able to reveal this site at the proper time. The phytomass-growth functions are obtained from biometric measurements [1–3], while in order to predict an increase in the phytomass, it is essential to use various imitation models which, by means of the so-called growth function, describe the state of crowns of trees, the growth of a separate tree, and their aggregation. Interpretation of the data of aerospace monitoring and design of the growth functions requires information on the characteristics of the heat- and mass transfer of combustible forest materials, such as the coefficients of specific heat c_p, thermal conductivity λ, moisture capacity c_m, and moisture conductivity λ_m. It is also impossible to perform mathematical simulation of physicochemical processes in forest phytocenoses without data on the characteristics of the heat and mass transfer of CFMs. The procedures for determining c_p and λ are given adequately in [4, 5]. Determination of the mass-transfer coefficients c_m and λ_m is based on the application of the theory of mass transfer in porous materials [6, 7].

In the present work, we investigate experimentally the mass-transfer processes in CFMs, such as needles of pine, cedar, and spruce, and also consider problems of drying (desorption) of CFMs and of moisture transfer.

Procedures for Determination of the Characteristics of CFMs. We conducted the desorption of the CFMs in a drying cabinet under isothermal conditions at temperatures of 22 ± 1^{o}C, 26 ± 1^{o}C, 33 ± 1^{o}C, and 42 ± 1^{o}C. The specimens of the CFMs of a certain mass m were placed at the prescribed time in the drying cabinet and were then weighed on a VLR-200 (ADV-200 M) analytical balance with an accuracy of 10^{-4} g. The decrease in the specimen mass $m - m_0$ characterizes the amount of moisture evaporated in the time of thermal action t. The weighing time does not exceed 0.5 min. To eliminate the systematic error which appears because of the cooling of the CFM specimens in the weighing time, we used a second portion of the CFMs of the same mass m that was weighed twice: at the beginning of the experiment and at the end of it. The systematic error in determining m does not exceed 0.7%.

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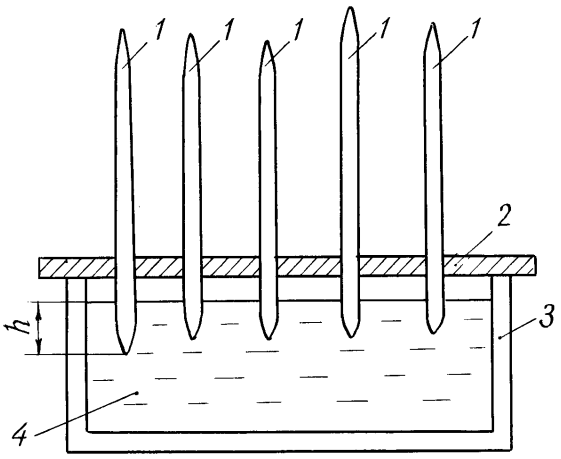


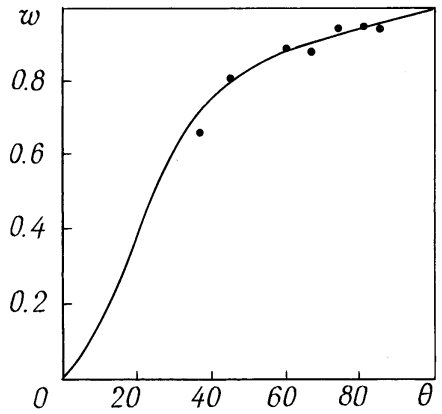


Fig. 1. Scheme of the experiments.

Fig. 2. Test check of a mass-exchange thermometer.

In the course of conducting these experiments, the relative air humidity W was controlled by means of an M-34 aspiration psychrometer, the atmospheric pressure P, by a BAMM-1 aneroid barometer, and the ambient-air temperature T, by a mercury thermometer. The total errors in determining the parameters did not exceed $\delta m \le 2.1\%$, $\delta T \le 3.8\%$, $\delta t \le 1\%$, $\delta P \le 3.7\%$, and $\delta W \le 6\%$. The moisture content of the CFMs $w = (m - m_0)/m_0$ was determined by weighing the moist CFM specimens and the specimens dried at $T = 100^{\circ}$C.

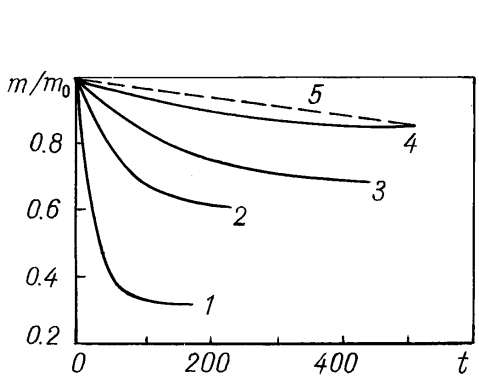
In investigations of the sorption of the CFM specimens, we placed individual needles (pine, cedar, and spruce), 10–20 pieces in a number, 1 (Fig. 1) on polyethylene substrate 2, which was installed into cuvette 3 filled with water 4. The depth of the CFM "fitting" h was $(3–4)\cdot10^{-3}$ m. Moreover, the sorption was conducted immediately in the ambient air with specimens that were previously dried at $T = 100^{\circ}$C. To determine the moisture capacity and moisture conductivity of the CFMs, we plotted the dependences of m/m_0 on time t from the results of weighing. The systematic error appearing because of the disturbance in the mass transfer at the time of weighing was eliminated by using several substrates with the CFMs in much the same way as for eliminating the systematic error in desorption.

By means of the X20 magnification of an MBS-9 microscope, visual representation of the internal structure of individual needles was carried out on individual replicas manufactured by cuts of midsections at different distances along the length of the needles.

The specific isothermal moisture capacity of the CFMs $c_m = (\partial w/\partial\theta)_T$ was determined according to the procedure of [7]. For this, special mass-exchange thermometers made of laboratory glass with ash-free filters (specifications 6-09-1678-86) were produced and a scale of the moisture-transfer potential $\theta = f(w)$ was constructed; the reference point of the scale corresponded to the minimum moisture content of cellulose.

The use of cellulose as the standard body was tested by comparing the known dependence $\theta(w)$ from [7] (the curve in Fig. 2) with the results obtained in the present work (the points). It is obvious that they are in satisfactory agreement with each other. Consequently, the moisture-transfer potential measured by the standard body (cellulose) uniquely characterizes the isothermal mass transfer of a liquid in a capillary-porous body.

The standard body (cellulose) was previously dried at $T = 100^{\circ}$C; then, wetted in water, it was placed in a thermometer with the CFM, closed on two ends, and in a thermostat until the hydrothermal equilibrium $\theta_c = \theta_n$ was established (θ_c and θ_n are the moisture-transfer potentials of the cellulose and needles measured in mass-transfer degrees $^{\circ}$M) [7]. The specific moisture capacity of the needles was determined from [7]: $m - m_0 = c_m m_0(\theta_2 - \theta_1)$, where θ_1 and θ_2 are the moisture-transfer potentials before the beginning of moisture exchange and at the end of it, respectively.



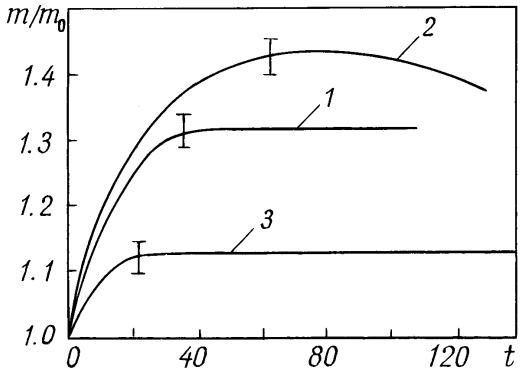


Fig. 3. Desorption of pine needles according to the scheme of Fig. 1. *t*, min.

Fig. 4. Sorption of needles according to the scheme of Fig. 1.

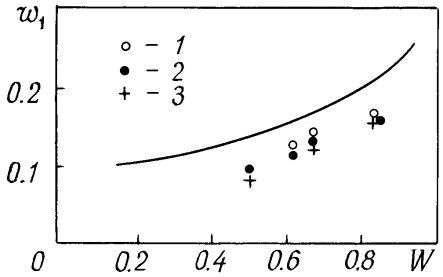


Fig. 5. Comparison of the CFM sorption with data obtained by G. S. Shubin.

The coefficient of specific moisture conductivity λ_m was determined from the law of moisture transfer [7] written for the isothermal conditions $j = \lambda_m \nabla\theta$, where $j = (m - m_0)/(S\Delta t)$ is the mass flux of moisture that is transferred through unit of the area of the needle S in the time interval Δt. The gradient of the moisture-transfer potential was determined as the arithmetic mean for various elements of the needles Δx along their length. Simultaneously, 5–20 needles were subjected to sorption.

The confidence intervals of the measurement results were calculated from the data of 3–6 observations with confidence probability 0.95.

Measurement Results. Figure 3 presents the typical dependences for the isothermal desorption of the specimens of the pine needles for m_0 = (1.24±0.12) g, W = (58.6±0.2)%, and w = (138.0±0.2)%. Here curves 1–4 were obtained at T = 96, 72, 52, and 30°C, respectively. Curve 5 reflects the isothermal sorption of the previously dried pine needles under conditions similar to those shown by curve 4.

Figure 4 shows the sorption curves of the needles following the scheme of Fig. 1. The experimental conditions are given in Table 1, where m_1 is the mass of one needle and N is the number of needles on the substrate.

It should be noted that after 24–36 h the amount of moisture in the CFM can decrease by 25–30%. The needles, submerged in water completely, continue to absorb moisture up to m/m_0 = 0.05–0.5.

Of interest are the results of comparison of the isothermal sorption of sawdust of pine, birch, spruce, and beech (the curve in Fig. 5 [8]) obtained at T = 20°C with the data for CFMs (pine needles 1; spruce needles 2; cedar needles 3). These results indicate that the needles of CFMs are less hydroscopic than wood sawdust.

Table 2 presents the results of determining the coefficient of specific moisture capacity of the CFMs, where δc_m is the confidence interval. For comparison, we give the data for the pine wood and lowland peat [7].

TABLE 1. Experimental Conditions

Type of CFM and No. of curve in Fig. 4	T, °C	P, mm Hg	W, %	w, %	l, cm	$d\cdot10^{-1}$, cm	m_1, g	N
Spruce, 1	21–22	743	79	152	1.4	0.7	0.00397	20
Pine, 2	26–22	734–740	79	14.06	3.5	1.0	0.00760	11
Cedar, 3	26	734–738	79	8.66	9–12	1.2	0.01632	10

TABLE 2. Results of Determination of c_m

Type of CFM	$c_m\cdot10^{-2}$, kg/(m·°M)	$\delta c_m\cdot10^{-2}$, kg/(m·°M)	Range of variation, θ, °M
Spruce	5.591	±0.820	590–750
Cedar	3.746	±0.571	400–580
Pine	8.723	±0.906	500–750
Pine wood	0.210	–	550–700
Lowland peat	1.200	–	300–550

TABLE 3. Results of Determination of λ_m

Type of CFM	λ_m, kg/(m·c·°M)	$\delta\lambda_m$, kg/(m·c·°M)	θ_2, °M	x/l
Spruce	$5.2\cdot10^{-6}$	$\pm0.71\cdot10^{-6}$	510	0.91
Cedar	$9.37\cdot10^{-5}$	$\pm0.86\cdot10^{-5}$	520	0.87
Pine	$1.098\cdot10^{-5}$	$\pm1.07\cdot10^{-5}$	505	0.89
Pine	$13.44\cdot10^{-5}$	$\pm0.97\cdot10^{-5}$	450	0.55
Pine	$17.63\cdot10^{-5}$	$\pm1.30\cdot10^{-5}$	400	0.21
Pine	$12.05\cdot10^{-3}$	–	300	0.89

Table 3 contains the results of determining the coefficients of specific moisture conductivity of the CFMs; x/l is the dimensionless distance reckoned from the base of a needle; θ_2 is the moisture-transfer potential of the CFM element.

The results presented in Tables 2 and 3 are obtained at T = (20–23)°C; W (82–95)%; P = (738–749) mm Hg.

Analysis of the Results Obtained. The needles of pine, cedar, and spruce trees are biological objects with a complex internal structure. The photograph of the midsection cut of living pine needles is given in Fig. 6a. One can see two conducting channels through which the capillary moisture transfer in sorption and desorption of the CFM occurs. The mouths (usually, twelve), located along the periphery of the cut, are micropores through which the moisture evaporates. The space between the envelope, the mouths, and the conducting channels is filled with cells between which the adsorption and diffusive-osmotic moisture exchange in micropores can occur. Consequently, the needles contain all types of bonds of moisture: adsorption, capillary-condensation, osmotic, and bound moistures in the cavities of the needle cells.

Another particular feature of the structure of the needles is that the density along their length is different: near the base of the needles the density is 1.2–1.3 times lower than at the top of them. Correspondingly, the diameters of the conducting channels are 1.5–2.0 times smaller, too. This feature of the structure with different porosity and density leads to the fact that the mass-transfer process is of an inhomogeneous nature along the length of the needles, while the needles themselves can be considered simultaneously as both a colloidal and a capillary-porous body.

In desorption and sorption of moisture, the structure of the needles changes. The cut of absolutely dry pine needles is shown in Fig. 6b. Two conducting channels are seen; the mouths and cells are atrophied. Figure 6c illustrates the cut of the typical midsection of pine needles, from which one can see the coalescence

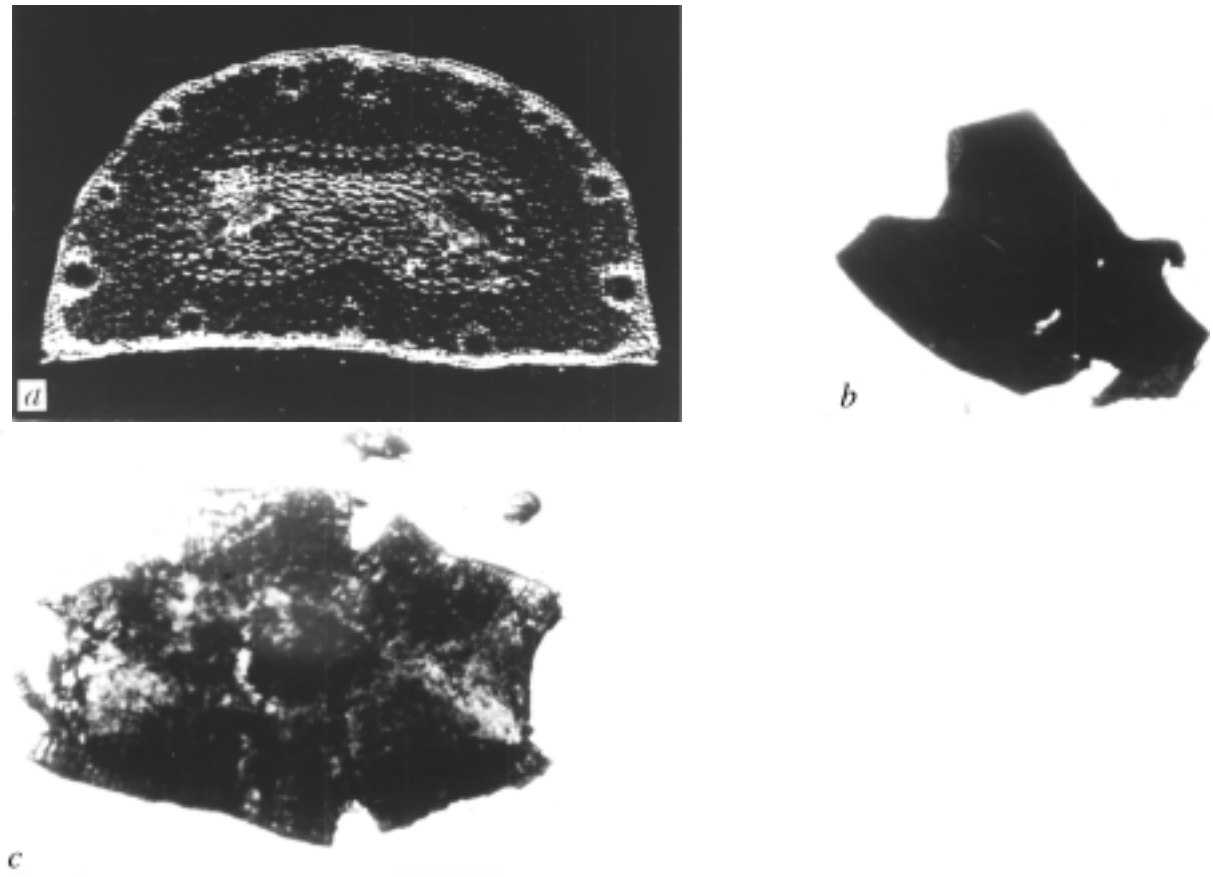


Fig. 6. Photographs of the midsection cut of the living needles of pine (a), dry needles after desorption (b), and swollen needles after sorption (c).

of two conducting channels of the pine needles into one large-diameter channel after the sorption of the CFM for 30 h. The moisture transfer is accompanied by shrinkage in desorption and swelling in sorption of water.

The analysis of the results presented in Fig. 3 indicates the strong dependence of the decrease in the moisture mass of the needles on the ambient-air temperature (curves 1–4). A comparison of curves 4 and 5 confirms the fact that the rates of drying and absorption of moisture by porous bodies are different [6–8], which is associated with additional expenditures of heat on moisture evaporation. With variation of the relative moisture of the air, the curves of isothermal soprtion and desorption of moisture form a hysteresis [7, 8].

The dependences given in Fig. 3 are widely used for determining the thermokinetic constants of drying of CFMs in mathematical simulation of the above processes [4, 5].

It is evident from the curves for the water sorption of the needles (Fig. 4) that the moisture transfer of water in the pine needles is more intense than in the needles of spruce and cedar; this fact is related to the internal structure of the needles and to the large values of the coefficients of specific moisture capacity and moisture conductivity (see Tables 2 and 3). The fraction of the capillary moisture of the pine needles is larger than that of spruce and cedar, which is confirmed by the comparison of the conducting channels on the replicas of the pine, spruce, and cedar needles. For a long period of time of moisture transfer (24–36 h), two conducting channels are combined into one large-diameter channel (see Fig. 6b and c), capillary forces become weak, and the liquid is displaced under gravity from the needles. The beginning of this process is shown in Fig. 4 (the decrease in m/m_0 on curve 2).

We should note that in the experiments the water sorption was conducted in immediate contact of the CFM with the liquid; therefore, the moisture content of the needles exceeded its maximum value during the

sorption of moisture from the air, which is related to the filling of microcapillaries and pores with moisture through the semipermeable cells of the walls and the internal volume and also to the osmotic absorption of the liquid [7, 8].

The analysis of the coefficients of specific moisture capacity and moisture conductivity (Tables 2 and 3) shows that the pine needles have the greatest values of c_m and λ_m, which is explained by the relatively higher content of capillary moisture and by the dimensions of the capillaries. The scatter in the experimental data is associated with the experimental conditions (dissimilar relative moisture and ambient air temperature). The considerable difference in the data for pine wood and peat, given for comparison in Table 2, is attributed to the fact that the wood and the peat took part only in the hygroscopic moisture transfer, while the needles of pine, spruce, and cedar were in immediate contact with the liquid.

It is seen from Table 3 that the coefficient of specific moisture conductivity of the CFM is not identical along the length of the needles and depends on the moisture-conductivity potential, which is explained by the inhomogeneity of the structure of the needles along their length.

The inhomogeneity of the structure of the CFM along the length of the needles and the experimental conditions, i.e., immediate contact of the needles with water, resulted in a paradox in determining λ_m and $\theta_1 < \theta_2$, where θ_1 and θ_2 are the moisture-transfer potentials of the lower and upper portions of the needles, i.e., $\nabla\theta < 0$. This phenomenon is explained by the fact that the moisture near the bottom of the needles, owing to the smaller diameter of the conducting channels, passes in transit to the top of the needles. The moisture content of the bottom of the needles is lower than the moisture content of the top.

CONCLUSIONS

1. The internal structure of CFMs (needles of pine, spruce, and cedar) has been studied and it has been established that the needles can be considered as a colloidal and capillary-porous body.

2. The procedure developed for determining the characteristics of mass transfer of CFMs is based on the application of the moisture-transfer potential and for the first time the coefficients of specific moisture capacity and moisture conductivity for certain CFMs have been obtained.

3. The processes of sorption and desorption of pine, spruce, and cedar needles have been investigated, and it has been established that a decrease in the pine needles occurs in desorption and their swelling in adsorption.

NOTATION

c_p, coefficient of specific heat; λ, coefficient of specific thermal conductivity; c_m, coefficient of specific moisture capacity; λ_m, coefficient of specific moisture conductivity; W, moisture; P, pressure; T, temperature; w, moisture content; t, time; θ, moisture-transfer potential at constant temperature; w_1, equilibrium moisture of the wood and the needles; S, space; m, mass; m_0, mass of dry needles; l, length of a needle. Subscripts: m, mass transfer; c, cellulose; n, needles.

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