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RATIONAL TECHNOLOGICAL REGIMES OF DRYING OF PACKETS OF SHOE UPPER MATERIALS

A. I. Ol'shanskii, E. F. Makarenko, and V. I. Ol'shanskii

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Maximum values of the Kirpichev mass transfer criterion have been obtained, experimental dependences for determining moisture diffusion coefficients have been found, and optimum regimes of drying of a packet of shoe upper materials have been determined.

Keywords: *Kirpichev mass transfer criterion, moisture diffusion coefficient, criterion of crack formation and warping, moisture-content field, rational regime of drying.*

Introduction. The process of drying of moist shoe upper materials is not only thermophysical but also technological, involving a change in the structural-mechanical, technological, and qualitative characteristics of finished footwear. On drying of packets of shoe upper materials, rational regimes are determined by technological properties and trends of their changes as a result of moisture removal and exposure to heat. The criterion of crack formation is taken to be the Kirpichev mass transfer criterion determined from a decrease in the moisture content during convective drying.

Problem Statement. Basic materials for manufacturing the shoe upper are various kinds of thermally stable and waterproof leathers and their substitutes on a par with the former in terms of protective, service, and physicohygienic properties. The shoe upper is manufactured mainly using leather of two groups: mostly chrome-tanned upper and lining leather for everyday footwear, and shoe Russian leather mostly tanned using combined methods [1].

In order to conduct experimental investigations and determine rational regimes of drying of packets, textiles and leather were selected [2, 3], from which packets of shoe upper materials were formed. As the upper material, use was made of thermally stable shoe Russian leather: thermoplastic was used as the toe material, thermoadhesive cotton cloth as the interlining materials, and ticking serge as the lining materials.

Leather has good elastoplastic and viscous properties which provide a reliable shape stability after stretching-lasting operations in shaping shoes on a last. The shape stability is largely affected by the shoe upper material representing a complex packet of various materials. Its outer layer can be genuine, artificial, or synthetic leather with the best elastoplastic properties and maximum shape stability.

Structural-mechanical properties of leather and packets of the shoe upper are influenced by all operations of leather manufacture and especially by drying, since, in drying, humidity has a primary effect on the shape stability. It has been found [4, 5] that, in drying, the development of a volumetrically stressed state inside the material results in crack formation, warping, and shape change because of nonuniform moisture-content distribution over the cross section of a moist body.

Discussion of the Experiment Designing. A. V. Luikov [4] suggested that the Kirpichev mass transfer criterion $\mathrm{Ki_m}$, which characterizes moisture-content fields, be regarded as the criterion of crack formation in drying. The choice is convenient in that $\mathrm{Ki_m}$ can be determined in various ways: from the evaporation rate $j(\tau)$, from the moisture-content difference $u_\mathrm{s} - u_\mathrm{c}$, and from the decrease in the moisture content over time, i.e.,

$$\mathrm{Ki_m} = \frac{j(\tau)\,R}{a_\mathrm{m}\rho_0\bar{u}_0} = 2\,\frac{u_\mathrm{s} - u_\mathrm{c}}{\bar{u}_0 - u_\mathrm{eq}} = 3\,\frac{\bar{u} - u_\mathrm{c}}{\bar{u}_0 - u_\mathrm{eq}}\,, \tag{1}$$

where u_eq is the equilibrium moisture content of the material, which can be neglected proceeding from temperature conditions of the experiment.

Vitebsk State Technological University, 72 Moskovskiy Ave., Vitebsk, 210035, Belarus; email: mef2007@yandex.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 82, No. 6, pp. 1075–1080, November–December, 2009. Original article submitted June 26, 2008; revision submitted June 1, 2009.

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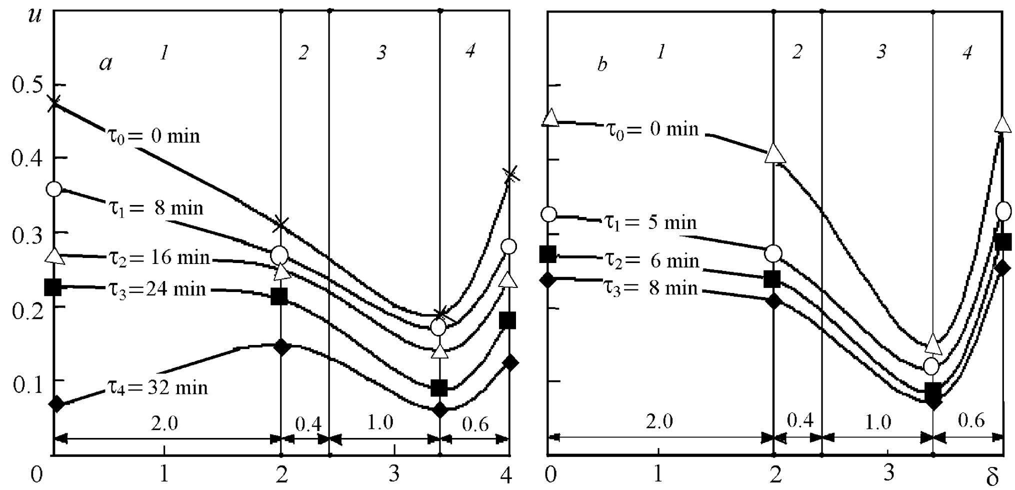


Fig. 1. Distribution of moisture contents across the packet thickness for two drying regimes: 1) Russian leather; 2) thermal cotton cloth; 3) thermoplastic; 4) knitted fabric. δ, mm.

It is impossible to calculate the moisture-content difference in the material from limiting shear stresses at which local destructions occur, since crack formation takes place in the elastoplastic region where Hooke's law [4] is not valid. The criterion Ki_m is determined most simply from the curve of the drying rate $j(\tau)$ and from the known moisture diffusion coefficient a_m. However, except for extremely incomplete information [5], experimental data on the moisture diffusion coefficient a_m for leathers are unobtainable. Therefore, Ki_m was basically determined from the moisture-content difference and the evaporation rate $j(\tau)$.

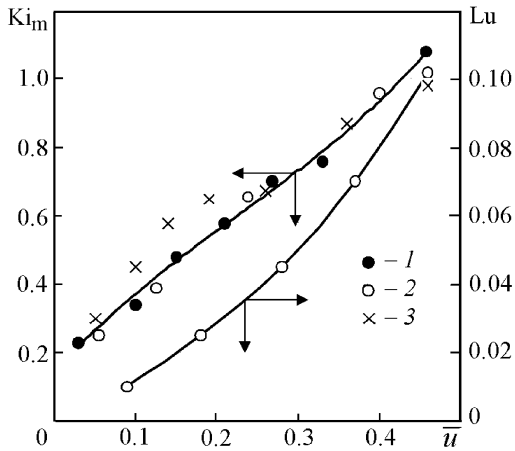
The mass transfer Kirpichev criteria Ki_m were determined from the moisture-content difference $u_s - u_c$ from the right-hand side of Eq. (1), and thereafter numerical values of $a_m = f(\bar{u})$ were found from the left-hand side of Eq. (1) with the aid of the experimental curve of the evaporation rate $j = f(\bar{u})$.

In order to determine maximum values of the Kirpichev criterion $Ki_m = f(\bar{u})$, at which crack formation and warping begin, a graph of the variation in the moisture diffusion coefficient $a_m = f(t_{med})$ is constructed, and thereafter a set of curves of the criterion $Ki_m = f(t_{med})$ is plotted, from which maximum values of $(Ki_m)_{max}$ at various moisture contents are obtained. The graph of the dependence $Ki_m = f(t_{med})$ allows one to outline a whole region of regimes at permissible Ki_m with a maximum drying rate, and optimum regimes themselves should be stepwise, i.e., as the moisture content of a body decreases, the temperature t_{med}, the air velocity v, and the drying rate should be increased [4]. Such a method of investigation is the most complete, providing a whole set of rational drying regimes. However, this is a fairly tedious process that requires a great many lengthy experiments for measuring moisture-content fields.

Experimental Technique. The problem of selecting an optimum temperature regime of drying was confined to packets of specimens of shoe upper materials with an initial moisture content u_0 = 0.46–0.48 at the air velocity v = 3–5 m/sec. For obtaining reliable results, each experiment was performed with a fivefold replication. Specimens were moistened by immersion in water with a temperature of 20°C up to u_0 = 0.46–0.48 followed by a 24-hour holding in the desiccator.

Moisture-content fields in the group of packets prepared for the experiment were not equalized before drying, since the central layer was thermoplastic with a low moisture conductivity. Moistening of packets before drying resulted in a parabolic distribution of moisture contents with differences between the surface and central layers $\Delta u = u_s - u_c$. The distributions of moisture contents across the packet thickness at various instants of time were constructed by a method of superposition. Six to eight packets prepared for the experiments were placed in the drying chamber and during drying were consecutively withdrawn from the chamber at equal time intervals τ = 8 min and laminated, and local moisture contents of each individual layer at a given instant of time were determined by a weight method. Simultaneously the volume-average temperature of the multilayer specimen was recorded.

Discussion of Experimental Results. Figure 1 presents the distribution of moisture contents across the packet thickness for two drying regimes: t_{med} = 90°C, v = 5 m/sec, and u_0 = 0.46 (a) and t_{med} = 120°C, v = 5 m/sec, and



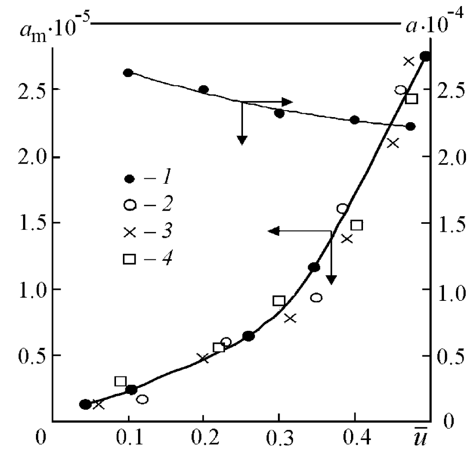


Fig. 2. Mass transfer criterion Ki_m and the Luikov criterion Lu as functions of moisture content of the packets of materials (t_{med} = 90°C, v = 5 m/sec, u_0 = 0.46, and δ = 4 mm): 1) calculation points according to N. E. Gorobtsova's equation; 2) same, according to V. I. Dubnitskii's equation; 3) same, according to V. P. Zhuravlyova's equation.

Fig. 3. Diffusion coefficients of moisture a_m and heat a as functions of moisture content of the material (t_{med} = 90°C, v = 5 m/sec, u_0 = 0.46, and δ = 4 mm): 1) calculation points according to N. E. Gorobtsova's equation; 2) same, according to V. I. Dubnitskii's equation; 3) same, according to V. P. Zhuravlyova's equation; 4) same, according to Eq. (2).

u_0 = 0.48 (b). It is seen from Fig. 1 that the convexity of parabolas of the distribution of moisture contents faces downward and the moisture-content difference $\Delta u = u_s - u_c$ is maximum in the beginning of the process. The period of constant-rate drying was observed only for the surface layer (Russian leather) for 4–5 min, and the moisture content of the layer changed here by Δu = 0.09–0.10 (Fig. 1a).

An important technological property of leather is the preservation of shape. In drying of leathers, as a result of a nonuniform structure of the face layer and the opposite layer (flesh side of hide) the moisture content of the first layer tends to be lower than that of the second; therefore, the difference in shear stresses between them at Δu_{max} causes warping of the face layer.

Figure 2 gives results of processing experimental moisture-content fields using Eq. (1). Maximum values of the Kirpichev criterion $(Ki_m)_{max}$ were observed in the initial period of drying with the maximum moisture-content difference between the surface and central layers Δu = 0.15 at the drying time $\tau \approx$ 8–10 min. Thereafter, in the same time periods, the moisture-content difference remained practically unchanged, Δu = 0.14–0.15, till the end of drying (Fig. 1).

With drying regimes t_{med} = 90°C and v = 3–5 m/sec with an initial moisture content u_0 = 0.46–0.48, no impairment of shape and warping of packets were fixed (Fig. 1a). With the drying regime t_{med} = 120°C, v = 5 m/sec, and φ = 5% (Fig. 1b), already in the initial drying period $\tau \approx$ 5–7 min the moisture-content difference across the packet thickness reached Δu = 0.25–0.26, and a flat surface of the packet rolled up on the side of the leather, and the packet laminated and lost shape already by the 6–8th min at drying. Maximum values of the Kirpichev criterion $(Ki_m)_{max}$ varied from 1.42 at the initial instant of drying, when breakdown of the packet structure and rolling up of the leather occurred, to 0.98–1.10 at the instant of time τ = 7–8 min when the packet was completely broken down and laminated.

The moisture diffusion coefficient a_m was determined from experimental values of the Kirpichev mass transfer criterion $Ki_m = f(\bar{u})$ and the drying rate $j = f(\bar{u})$.

Figure 3 presents the dependence $a_m = f(\bar{u})$ for shoe upper packets. Reliability of the values of a_m obtained for leather was checked using the equation

$$Fo_m = \frac{a_m \tau}{R^2} = Fo\,Lu = \frac{a \tau a_m}{R^2 a}\,. \qquad (2)$$

The thermal diffusivity was taken from experimental data of E. A. Miroshnikov [5] based on the dependence $\lambda = f(u)$ for Russian leather. The dependence $a = f(\overline{u})$ is presented in Fig. 3. The Fourier heat transfer criterion Fo and the Luikov criterion Lu were determined from experimental data, and thereafter the diffusion coefficient $a_{\mathrm{m}} = f(u)$ was obtained from the Fourier mass transfer criterion $\mathrm{Fo_m}$. All calculation points for a_{m} determined from Eq. (2) are in favorable agreement with the experimental curve for $a_{\mathrm{m}} = f(\overline{u})$. The Luikov criterion varied from 0.01 to 0.11 (Fig. 2).

A continuous increase in the moisture diffusion coefficient a_{m} with increase in the moisture content $\overline{u}$ is characteristic of a variety of colloidal capillary-porous materials [4]. Experimental data relating to the moisture diffusion coefficient for many materials are fairly well described by empirical equations of N. E. Gorobtsova, V. I. Dubnitskii, and V. P. Zhuravlyova [4, 6].

Since expression (1) for the mass transfer criterion $\mathrm{Ki_m}$ is valid for a single-layer body, the possibility of using it for a multilayer body was verified by a designed experiment, which was a check one in character. A specimen consisting of two compacted layers of Russian leather with face surfaces facing out and with a total thickness $\sigma = 4$ mm was dried together with multilayer specimens. Experimental data for the moisture diffusion coefficient for Russian leather $a_{\mathrm{m}} = f(\overline{u})$ were practically the same as those for multilayer specimens. Discrepancies of numerical values for $a_{\mathrm{m}} = f(\overline{u})$ lay within the experimental accuracy (5–10%).

Analysis of Experimental Investigations. Experimental data for colloidal capillary-porous materials are satisfactorily described by N. E. Gorobtsova's equation [6]

$$\frac{a_{\mathrm{m}0}}{a_{\mathrm{m}}} = 1 - A\rho_0\overline{u}\,, \tag{3}$$

where $A = 0.0019$ for colloidal capillary-porous bodies. Experimental data of V. I. Dubnitskii and V. P. Zhuravlyova are in good agreement with empirical equations

$$\frac{a_{\mathrm{m}0}}{a_{\mathrm{m}}} = 1 - D_0\overline{u}\,, \tag{4}$$

here $D = 0.002\rho_0$,

$$\frac{a_{\mathrm{m}0}}{a_{\mathrm{m}}} = 1 - D\overline{u}\,, \tag{5}$$

where $D = 2\dfrac{\rho_0}{1000}$ for colloidal capillary-porous bodies. The coefficient a_{m} entering into all equations is related to the body's temperature as follows:

a) in N. E. Gorobtsova's equation

$$a_{\mathrm{m}0} = a_{00}B_0\left(\frac{T}{1000}\right)^{n}, \tag{6}$$

b) in V. I. Dubnitskii's equation

$$a_{\mathrm{m}0} = a_{00}B\left(\frac{T}{1000}\right)^{n}, \tag{7}$$

and c) in V. P. Zhuravlyova's equation

$$a_{\mathrm{m}0} = a_{00}M\left(\frac{T}{1000}\right)^{n_0}. \tag{8}$$

With colloidal capillary-porous bodies the constants $B_0 = B = 1$, $n = 10$, $M = 10^{-15}$, and $n_0 = 20$ are the case.

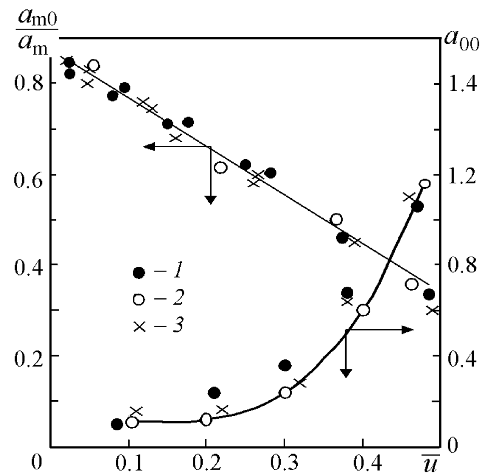


Fig. 4. a_{m0}/a_m and a_{00} as functions of the moisture content $\bar{u}$ for packets of Russian leather. Designations 1–3 are the same as in Fig. 2.

Thus, the moisture diffusion coefficient a_m for moist materials is determined depending on the kind of body, its moisture content, and temperature.

Figure 4 plots a_{m0}/a_m and a_{00} as functions of $\bar{u}$ for packets of Russian leather. Clearly, the dependence $a_{m0}/a_{00} = f(\bar{u})$ is linear, and the dependence $a_{00} = f(\bar{u})$ is described by an exponent. Processing and analysis of experimental data for drying of packets of Russian leather showed that the constant a_{00} in Eqs. (6)–(8) is a function of moisture content and is described by the empirical dependence

$$a_{00} = 0.035 \exp (7.25\bar{u}) , \tag{9}$$

which connects empirical dependences (3)–(5). Calculation points obtained from these equations lie on the same curve to a sufficient degree of accuracy (Fig. 3).

We next consider the effects of individual similarity criteria on heat and moisture transfer in drying with constant-rate mass transfer [7]. The largest effect is exerted on heat and mass transfer by the criteria $\mathrm{Ki_m}$ and Lu. We write Eq. (2) in the form

$$\frac{\mathrm{Fo_m}}{\mathrm{Fo}} = \frac{a_m}{a} = \mathrm{Lu} . \tag{10}$$

At small values of the Luikov criterion Lu = 0.01–0.1, the field of heat transfer (temperatures) propagates much more rapidly than does the moisture-content field, i.e., the material heating is more rapid than a change in the difference in moisture contents between the surface and central layers.

The surface criterion of mass transfer $\mathrm{Ki_m}$ has the greatest influence on the moisture-content field. With increase in the Kirpichev mass transfer criterion $\mathrm{Ki_m}$ the mass transfer potential increases by a linear law [7].

Conclusions. The performed experimental investigations and analysis of the data for drying of Russian leather packets for the shoe upper allowed establishing dependences for the moisture diffusion content for Russian leather packets and the rational temperature regime t_{med} = 90^{o}C and v = 5 m/sec at $\bar{u}_0$ = 0.48, since at maximum values of the Kirpichev criterion $(\mathrm{Ki_m})_{max} \approx 1.42$ with the drying regime t_{med} = 120^{o}C, v = 5 m/sec, and $\bar{u}_0$ = 0.48 the material warped and its shape was completely broken down.

NOTATION

A, D, D_0, B, B_0, M, and a_{00}, constants determined experimentally; a_m and a_0, diffusion coefficients of moisture and heat, m^2/h; $j(\tau)$, evaporation rate, kg/(m^2·h); $\mathrm{Fo_m}$ and $\mathrm{Ki_m}$, Fourier and Kirpichev mass transfer criteria; Fo and Lu, Fourier and Luikov heat transfer criteria; R, characteristic dimension of the specimen, m; t_{med}, temperature of the medium, ^{o}C; v, velocity of the heat-transfer agent, m/sec; u_s and u_c, moisture content on the surface and at the center of the specimen; u_0, $\bar{u}$, and u, initial, average, and local moisture content of the body; Δu, moisture-content difference across the specimen thickness; δ, material thickness, mm; λ, thermal conductivity, W/(m·deg); ρ_0, density of the absolutely dry body, kg/m^3; τ, drying time, h; φ, relative humidity of air, %. Subscripts: med, medium; s, surface; c, center; max, maximum; 0, initial state; m, mass transfer.

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