MODEL OF DRYING MECHANISM OF THE CHLOROPRENE LATEX FOIL AND ITS RELATION TO EXPERIMENTAL RESULTS

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Theoretical model of convective drying is proposed for the chloroprene latex foil, which is the intermediate product in the production of chloroprene rubber. The model is based on the assumption that drying of this material takes place as evaporation from the free bed surface at steadily decreasing evaporation surface. This assumption is in agreement with the fact that drying at the beginning of the process takes place in the period of decreasing velocity but, nevertheless, it is effected by external hydrodynamic conditions. Theoretical and experimental results are compared and the suitability of the model is discussed. It is possible to expect that drying of latex foils, coats and films of another origin has a similar mechanism and that the obtained results have a large variety of application.

The chloroprene latex foil is the intermediate product in the production of neoprenes of the foil type[1]. It originates by freezing of the latex emulsion. After drying the foil formed by the coagulated latex is irreversibly altered into rubber. Due to specific structure and geometrical properties of the foil namely its very small thickness (maximum about 1·5 mm) in the direction of moisture transfer with respect to dimensions in other directions, the drying of the material differs from processes appearing in the majority of industrially dried materials[2-4]. The difference rests mainly in the considerable effect of external hydrodynamic conditions though the process takes place from the beginning in the period of decreasing drying rate.

The coagulated latex consists of discrete particles of spherical shape whose mean diameter is within the range from 0·12 to 0·13 μm[5-7]. In a certain sense the coagulated latex is a layer of spherical particles with a considerable porosity, while the void volume is filled with the dispersing liquid, mostly water[5,8]. By use of the electronic microscope it has been demonstrated that in a fresh coagulate the particles mostly are not in contact until the humidity does not decrease below about 13%[5,6,9]. With continuing drying the particles move closer together, their shape is deformed and they fill the void volumes after moisture escape. Finally they merge into a compact mass. The external manifestation of these changes is the uniform contraction of the material in all directions.

THEORETICAL

In derivation of the model the following assumptions are made: *a*) the material consists of discrete spherical particles of the diameter equal to the mean diameter of the system of latex particles; *b*) the moisture is present only in the liquid state and only in the void space among the particles, porosity thus depends only on moisture; *c*) surface area of latex particles is constant in spite of their deformation; *d*) the change to the compact layer, related to the decay of discrete particles is sudden; *e*) the evaporation surface is always on the level of the surface layer of particles; *f*) equilibrium content of moisture in the material at the operating parameters of the drying media is negligible; *g*) the change in physical properties of the system is negligible; *h*) the latex foil is flat plate shaped, and the evaporation from its side walls in negligible; *i*) the layer is equivalent to the system of parallel elastic capillaries of circular cross sectional area, the diameter of which equals to the quadruple of the hydraulic radius of the particle layer and their length is proportional to the height of the layer *i.e.* to the thickness of the foil.

It results from these assumptions that the latex foil, which is identical to the layer of spherical latex particles, can be in any moment alternated by a system of fictive capillaries whose diameter and length decreases with decreasing moisture content. The elastic capillaries do shrink due to the evaporation of water and they steadily press the surface of water on the level of capillaries ends. If, in agreement with the assumption (*c*) the surface area of latex particles is constant, the wetted surface of fictive capillaries must also be constant. Consequently, regarding the mentioned dependence of the capillaric diameter and length from the humidity, the number of capillaries must change with the moisture content. In other words the dried material is represented in each moment of drying by another system of capillaries.

Let g_u be the mass of the moist material with the unit mass of latex g_0 and thus the mass of moisture numerically equals to the moisture u, so that

$$g_u = g_0 + u \,, \tag{1}$$

while

$$g_0 = 1\ \text{kg} \,. \tag{2}$$

The void volume between the particles equals to the moisture volume. There thus holds

$$V_u = u/\varrho \,. \tag{3}$$

The wetted surface area is equal to the surface area of particles

$$S_m = n\pi d_p^2 \,. \tag{4}$$

Then the diameter of fictive capillaries, in agreement with the stated assumption and with respect to the definition of hydraulic radius equals to

$$d_u = 4V_u/S_m . \tag{5}$$

By substitution of Eqs (3) and (4) into (5) the diameter of fictive capillaries is obtained in the form

$$d_u = 4u/\varrho n\pi d_p^2 . \tag{6}$$

The number of latex particles is expressed as

$$n = 6g_0/\varrho_s\pi d_p^3 . \tag{7}$$

By substitution of Eq. (7) into (6) the diameter of capillaries is given by the relation

$$d_u = 2\varrho_s d_p u/3\varrho g_0 . \tag{8}$$

At two side drying of the material there holds for the evaporating surface with respect to the assumption on the system of fictive capillaries

$$S_u = 2m_u\pi d_u^2/4 . \tag{9}$$

According to the made assumptions the length of considered capillaries is proportional to the thickness of the foil

$$H_u = kh_u = k\,2\delta_u . \tag{10}$$

The evaporating surface, equal to the diameter of capillaries is then given by the relation

$$S_u = 2u/kh_s\varrho . \tag{11}$$

For number of capillaries by comparison of Eqs (9) and (11) the relation is obtained

$$m_u = 9\varrho g_0^2/\pi\varrho_s^2 d_p^2 kh_u u . \tag{12}$$

From the uniform contraction of material during the drying, results the validity of the relation

$$h_u = h_s(1 + \varrho_s u/\varrho g_0)^{1/3} . \tag{13}$$

By introduction of quantities

$$A = 2/kh_u\varrho \tag{14}$$

and

$$B = \varrho_s/\varrho g_0 \tag{15}$$

with the combination of Eqs (*11*), (*13*), (*14*) and (*15*) the relation for the evaporating surface is obtained

$$S_u = Au/(1 + Bu)^{1/3}\,. \tag{16}$$

For the drying rate, it is possible to write

$$-\mathrm{d}u/\mathrm{d}\tau = \psi S_u(p'' - p_f)\,, \tag{17}$$

or with respect to Eq. (*16*) the relation is obtained

$$-\frac{\mathrm{d}u}{\mathrm{d}\tau} = \frac{A\,\psi(p'' - p_f)u}{(1 + Bu)^{1/3}}\,. \tag{18}$$

From the rate equation (*18*) results that the drying rate is decreasing and the hydrodynamic conditions considerably affect the drying rate due to their effect on the mass transfer coefficient ψ.

The partial pressure of water vapours in the medium and the mass transfer coefficient practically do not change at the given temperature and moisture of the drying medium and the given flow rate. The pressure of saturated water vapour depends only on temperature. If we consider the temperature of the material to be constant (except the initial stage of the operation) and if the change in thickness is neglected (A = const) it is possible to write

$$A\,\psi(p'' - p_f) \approx K(t_f, \mathrm{w})\,, \tag{19}$$

or for the given temperature and velocity of the drying medium

$$K = \text{const.} \tag{20}$$

Eq. (*18*) takes in this case the form

$$-\frac{\mathrm{d}u}{\mathrm{d}\tau} = K\,\frac{u}{(1 + Bu)^{1/3}}\,. \tag{21}$$

After integration from $u = u_0$ to $u = u$ and from $\tau = \tau_0$ to $\tau = \tau$ the relation for the drying time is obtained

$$\tau = \frac{3}{K}\left\{(z_0 - z) + \ln\left[\frac{(z_0 - 1)}{(z - 1)}\sqrt{\frac{z^2 + z + 1}{z_0^2 + z_0 + 1}}\right]^{1/3} - \frac{1}{\sqrt{3}}\left(\operatorname{arctg}\frac{2z_0 + 1}{\sqrt{3}} - \right.\right.$$
$$\left.\left. - \operatorname{arctg}\frac{2z + 1}{\sqrt{3}}\right)\right\}, \qquad (22)$$

where

$$z_0 = (1 + Bu_0)^{1/3}, \qquad (23)$$

$$z = (1 + Bu)^{1/3}. \qquad (24)$$

The value of the constant K can be determined from the experimental data. Further simplification is based on the assumption that the inequality

$$1 \gg Bu. \qquad (25)$$

is satisfied.

The higher is the temperature of the drying medium the more probable is that the inequality (*25*) is satisfied during the major part of the operation due to the fast decrease of the moisture content to very low values.

In the considered case Eq. (*21*) takes the form of the first order rate equation

$$-\mathrm{d}u/\mathrm{d}\tau = Cu \qquad (26)$$

and after integration in corresponding limits the relation for the time dependence of moisture is obtained

$$u = u_0 \exp(-C\tau). \qquad (27)$$

EXPERIMENTAL

The drying curves of the chloroprene foil were determined by the derivatograph OD-102 MOM. For heating of the samples to the required temperature the thermostate oven was used, enabling to keep the selected temperature of the studied compound with an accuracy of ±1°. The changes in mass were recorded in dependence on time and were determined with an accuracy up to 1% of the original sample weight. The velocity of the drying medium around the dried material was very small ($w_f < 2$ m/s).

RESULTS AND DISCUSSION

The experimental drying curves obtained at the temperature of the drying medium 75, 85, 90, 100, 110 and 120°C together with the shape of theoretical dependences corresponding to Eq. (*22*) are plotted in Fig. 1. The value of constant K was determined from the experimental data. In Fig. 2 is the analogous comparison of experimental results with the theoretical dependence corresponding to Eq. (*27*).

The agreement of theoretical and experimental values improves with the increasing temperature of the drying medium in the case of both equations. This fact is understandable with respect to assumptions expressed by Eq. (*19*) or by inequality (*25*). It is also understandable that experimental values corresponding to initial phases of the operation are not in agreement with the theoretical shape of the drying curve. The mentioned disagreement is also due to the fact that the surface of the material is corrugated by irregular "channels" and "craters". The moisture present in these cavities has a differing bond with the skeleton than the rest of the moisture.

Deviation of experimental data from the theoretical dependence of drying curves which is obvious also in their central part (especially at temperatures 75, 85 and 90°C of the drying medium) could be the result of incomplete validity of the made assumptions *e.g.* of the assumption that the whole moisture is in the void space between the particles. It was determined[10,11] that actually just at temperatures 80 – 90°C there can be relatively significant part of water dissolved in the latex mass. Similar reasons can cause the deviation of experimental data from thoretical dependences nearly in all cases in the final phases of the operation.

But in general it is possible to state that the agreement of the obtained experimental data with the theoretical dependence of drying curves is very good. From the practical point of view both equations (*22*) and (*27*) are equivalent. At lower temperatures

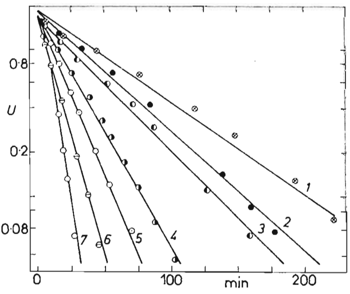

FIG. 1

Comparison of Theoretical Drying Curves ——, (calculated according to Eq. (*22*)) with Experimental Data

Experiment	t_f, °C	K, min^{-1}
1	75	$1{\cdot}76 \cdot 10^{-2}$
2	85	$2{\cdot}16 \cdot 10^{-2}$
3	90	$2{\cdot}38 \cdot 10^{-2}$
4	100	$4{\cdot}14 \cdot 10^{-2}$
5	110	$5{\cdot}61 \cdot 10^{-2}$
6	120	$8{\cdot}54 \cdot 10^{-2}$
7	130	$14{\cdot}22 \cdot 10^{-2}$

of the drying medium the agreement of experimental and theoretical value is slightly better when Eq. (*22*) is used, at temperature 110 and 120°C the agreement is better when Eq. (*27*) is used which is unexpected. This is obviously partially affected by the fact that the value of constant K was calculated as the arithmetic mean of values K_i calculated from Eq. (*22*) for individual τ_i and z_i while the value C was calculated by the least square method on basis of values $\log u_i$ and τ_i.

The used experimental apparatus did not enable to perform experiments at higher velocities of the drying medium. The velocities of the drying medium (air) were at lower limit which just garanteed the withdrawal of vapours of the moisture from the space at the surface of the material. A similarly good agreement of theory with the experiment could have been expected also at higher velocities of the drying medium

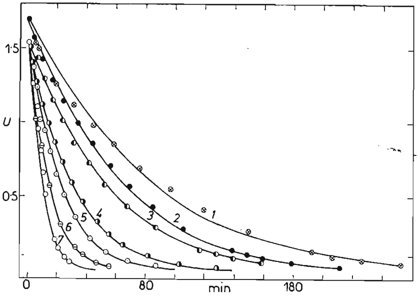

FIG. 2

Comparison of Theoretical Drying Curves ——, (calculated according to Eq. (*27*)) with Experimental Data

Experiment	t_f, °C	C, min^{-1}
1	75	$0{\cdot}61 \,.\, 10^{-2}$
2	85	$0{\cdot}815 \,.\, 10^{-2}$
3	90	$0{\cdot}92 \,.\, 10^{-2}$
4	100	$1{\cdot}58 \,.\, 10^{-2}$
5	110	$2{\cdot}17 \,.\, 10^{-2}$
6	120	$3{\cdot}37 \,.\, 10^{-2}$
7	130	$5{\cdot}48 \,.\, 10^{-2}$

i.e. at conditions of convective drying of the latex foil in practice. On basis of experimental results[2,3] it is possible to foresay for these conditions that with the increasing velocity of the drying medium the value of constant K in Eq. (*22*) or of the constant C in Eq. (*27*) will increase. It is obvious that the values of these constants are increasing with the temperature of the drying medium, but this dependence has not been studied within this work.

Values of constants K or C must be determined from experimental data. They could be approximately estimated on the basis of relation (*19*) either if the value of the proportionality constant is estimated from Eq. (*10*) or if suitable relations are available for calculation of the mass transfer coefficient and vapour pressure.

Quantitative agreement of experimental and theoretical results is very good especially from the point of view of practical application of the obtained results and enables to expect that it would be possible to use them for higher velocities of flow around the material by the drying medium and for drying of latex films and foils of another origin.

Validity of the proposed model is obviously limited to materials of very small thickness, *i.e.* to very small dimensions in the direction of mass transfer in comparison with other dimensions. Only in this case is acceptable the made assumption on continuous squeezing of the water surface on the level of the geometric surface of the dried foil.

LIST OF SYMBOLS

A	quantity defined by Eq. (*14*)	$L^2 M^{-1}$
B	quantity defined by Eq. (*15*)	M^{-1}
C	constant in Eqs (*26*) and (*27*)	τ^{-1}
d_p	diameter of the latex particle	L
d_u	diameter of fictive capillary	L
g_0	unit mass of dry material	M
g_u	mass of moist material, containing unit mass of dry material	M
h_s	roughness of dry foil	L
h_u	roughness of moist foil	L
k	proportionality constant, defined by Eq. (*10*)	
K	constant in Eqs (*21*) and (*22*)	τ^{-1}
m_u	number of fictive capillaries	—
n	number of latex particles	—
p''	vapour pressure of water	$M L^{-1} \tau^{-2}$
p_f	partial pressure of water vapours in the stream of drying medium	$M L^{-1} \tau^{-2}$
S_m	surface area of latex particles	L^2
S_u	evaporating surface	L^2
t_f	temperature of the drying medium	T
u	mass of water in the considered amount of material, numerically equal to the moisture	M
u_0	initial mass of water in the considered amount of material, numerically equal to the initial moisture	M

w_f	velocity of the drying medium	$L\,\tau^{-1}$
V_u	void volume in the bed of latex particles	L^3
z	quantity defined by Eq. (*24*)	
z_0	quantity defined by Eq. (*23*)	
δ_u	half thickness of moist foil	L
ϱ	density of water	$M\,L^{-3}$
ϱ_s	density of latex particles	$M\,L^{-3}$
ψ	mass transfer coefficient	$\tau\,L^{-1}$
τ	time	τ

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