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DIFFUSION IN A POROUS SYSTEM IN CROSSED ELECTRIC AND MAGNETIC FIELDS

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Diffusion in crossed electric and magnetic fields is considered; measurements are reported on accelerated diffusion in the extraction of low-molecular-weight fractions (hemicelluloses) from cellulose and of copper salts from viscose fiber.

Extraction from capillary systems into surrounding liquids is an important general process in mass transfer; examples are elimination of copper salts from viscose fiber by washing the fiber with sulfuric acid [1] and extraction of low-molecular-weight fractions (hemicelluloses) from cellulose with caustic soda during mercerizing [2, 3].

Considerable interest attaches to the use of various fields, including electromagnetic ones, in liquids to accelerate diffusion in such systems; in particular, crossed electric and magnetic fields may be employed. Here we consider the rates of diffusion processes under such conditions and present some measurements.

The external-diffusion rate is controlled by the hydrodynamic conditions around the dispersed phase, and that rate may be increased by efficient mixing [4, 5], as well as by mechanical oscillation (ultrasound, vibration, etc.) [6], and by magnetic [7] or electric [8-10] fields.

It has been shown [8-10] that an electric field in a conducting liquid produces a flow of the liquid near a local solid, liquid, or gaseous inclusion because the magnetic field arising from the current interacts with the liquid. More vigorous flows arise near such particles in crossed electric and magnetic fields [11-14]. Also, flows arise in a very narrow range within the boundary and ordinary diffusion layers because the electric double layer at the interface interacts with the crossed fields [15]. One naturally expects that all these various flows will substantially accelerate mass transfer, and as a result one will obtain conditions close to ideal mixing in the external-diffusion region.

The current density in the liquid, and the distribution between and within the particles, may be dependent on the effective conductivities of both media. Methods of estimating effective conductivity for porous systems have been surveyed [16], and it has been shown that the value is dependent on the conductivity of the skeleton in a particle and on that of the liquid within the porous structure, as well as on the structure of the skeleton. The case where σ_{ef} for the particles is related to σ_l for the liquid by ($\sigma_l \leq \sigma_{ef}$) is of only theoretical interest, since the converse applies in nearly all practical cases. As a result, the current density within the particles is nearly always substantially less than that in the liquid ($j_l \gg j_p$). If the system is in a uniform external magnetic field, the density of the electromagnetic forces f acting on the liquid phase outside a particle is substantially

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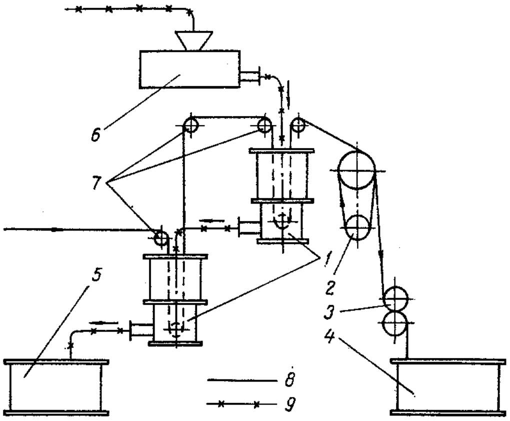

Fig. 1. The apparatus: 1) separating equipment within solenoid; 2) device for transporting a bundle of viscose fibers; 3) compression device; 4) tank containing softened water for removing acid from fiber; 5) acid drain tank; 6) acid pressure-head tank; 7) rollers for transporting fiber bundle; 8) fiber bundle; 9) acid.

greater than the same f_p within a particle ($f \gg f_p$), and the additional pressure in the surrounding liquid P_1 due to these forces follows the law

$$P_1 = fy,$$

where y is the current coordinate along the direction of the electromagnetic forces. The pressure in the liquid within the particle is

$$P_2 = f_p y.$$

Then a layer at a distance Δy from the surface experiences the pressure gradient

$$\Delta P = (f - f_p)\Delta y. \tag{1}$$

This causes the liquid to move through the particle structure; the direction of motion is dependent on the direction of the pore or capillary, while the mean direction is against the direction of the electromagnetic forces.

The general motion of the liquid under the pressure gradient combines with molecular diffusion to produce a diffusion-flux density in a particle in this case of [4, 5, 17]

$$j = -D_1 \frac{\partial c}{\partial x} + vc. \tag{2}$$

The speed v of the liquid in the structure can be estimated [18-20] by considering the kinetics of the magnetohydrodynamic forces and the capillary size, in conjunction with the geometry, concentration and rheological characteristics of the electrolyte, and the extent of the electric double layer.

The concentrations of the diffusing substances within a particle are [3, 4, 16] given by

$$\frac{\partial c}{\partial t} = -\frac{\partial (vc)}{\partial x} + \frac{\partial}{\partial x}\left(D_c \frac{\partial c}{\partial x}\right). \tag{3}$$

The solutions to (3) for various cases of diffusion have previously been considered [21]; one can usually assume that the concentration in the liquid around a particle is negligible in comparison with that within a particle, while ideal mixing occurs in the external medium; thus, one can estimate the rate of extraction from a porous system in the presence of internal convection by using the solution to (3) derived for the planar case in [22]. At the start, all the material is located within a planar film (plate), while the coordinate axis is directed from the surface of the film inward, whereupon the initial and boundary conditions take the following form: $x > 0$ and $c = c_0(x)$ for $t = 0$; $c = 0$ for $x = 0$ (surface of film).

TABLE 1. Relative Residual Copper Content in Viscose Fiber

Extraction time, sec	Crossed fields, f = $5 \cdot 10^2$ N/m^3	Control experiments	
		usual conditions	with transverse flows
2,8	0,07	0,26	0,13
5,6	0,01	0,05	0,04

TABLE 2. Distribution of Magnetic Induction, Current Density, and Electromagnetic-Force Density over the Diameter of a Cylinder

Distance from center R, m	Field induction, T	Current density in liquid, 10^4 A/m^2	Electromagnetic-force density, $10^4 \cdot$ N/m^3
0,02	0,215	0,93	0,20
0,04	0,235	0,47	0,11
0,06	0,260	0,31	0,08

The concentration within a film of thickness 2δ should [22] be proportional to $\exp(2\delta v)$, whereas the relationship is $\exp[-S(Dt/\delta^2)]$ for ordinary molecular diffusion [4, 5, 17], i.e., the internal flow in the structure in crossed fields should cause the processes to be much more rapid than those for ordinary molecular diffusion.

The measurements on extracting copper from viscose fiber with sulfuric acid were performed with the apparatus shown in Fig. 1, which consists of several major sections; the solenoids, transport device, system of tanks, and power supply. A working vessel is placed within each of the solenoids (treatment bath), and this contains flat lead electrodes. A bunch of the viscose fibers is passed successively to the first and second parts of the equipment, where the copper salts are extracted.

The nonuniformity of the bunch along the length and across the cross section cannot be controlled strictly, and so it was minimized by selecting an appropriate observation range along the length for which the dispersion of the measured quantity was homogeneous. This range was taken as 20-30 m. Then a constant speed of 0.68 m/sec required 10-15 analysis samples for such a range. The method of selecting finished fiber for analysis for copper by the iodine method involves taking samples at intervals of 1.6 m, each sample being of length 0.4 m.

The acid concentration c was always 300 g/liter, while the time of contact with the acid was 2.8 sec (one section) or 5.6 sec (two sections). The field induction B (approximately 0.25 T) and the current density in the liquid (j approximately $2 \cdot 10^3$ A/m^2) were kept constant, i.e., the electromagnetic-force density in the liquid f was constant at approximately $5 \cdot 10^2$ N/m^3.

Two series of checks were performed. In the first case, the fiber bundle moved in a working vessel at 0.68 m/sec, while in the second the speed was the same, but additional transverse jets were present. The temperature of the acid in all cases was constant at 45°C.

Table 1 gives mean copper contents for the viscose fiber from 25-30 analyses for the treatments in crossed fields and in the control tests.

Little is known about this system, so one can only say that there is a qualitative difference between the diffusion in the crossed fields and that in the control case. Table 1 shows that the crossed fields with f of approximately $5 \cdot 10^2$ N/m^3 accelerated the extraction of copper salts from the fiber by comparison with the control experiments, as would be expected.

The tests on extracting low-molecular-weight hemicellulose fractions from cellulose were performed with laboratory equipment consisting of a solenoid of length 0.5 m and internal diameter 0.17 m, which contained a coaxial cylinder, whose walls were the electrodes (outside diameter 0.15 m and inside diameter 0.01 m), while the bottom was made of an insulator. The solenoid was placed within a steel body (st. 3 steel) to reduce the circuit reluctance.

The extent of extraction of the hemicellulose was determined with the following as variables: working time, weight proportions of caustic soda and air-dried cellulose (bath modulus), fields, and degree of compression.

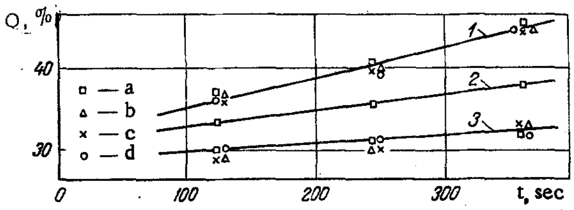

Fig. 2. Kinetics of extraction for low-molecular-weight fractions from cellulose for reduction in bundle size by a factor of 3.44: 1) in crossed electric and magnetic fields; 2) in an electric field with stirring; 3) in an electric field without stirring; a-d) bath moduli: a) M = 6; b) 8; c) 10; d) 15.

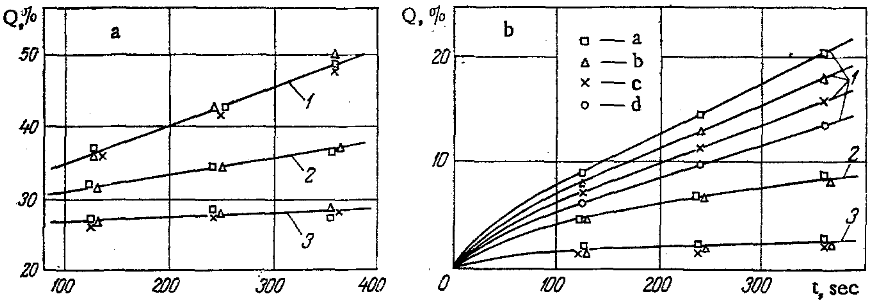

Fig. 3. Extraction of low-molecular-weight fractions from cellulose with: a) 2.94 reduction factor; b) no squeezing; 1) in crossed electric and magnetic fields; 2) under ordinary conditions with stirring; 3) under ordinary conditions without stirring; a) M = 6; b) 8; c) 10; d) 15.

A weighed amount of the cellulose was placed in the coaxial cylinder and treated with the appropriate amount of solution as defined by the bath modulus. The current was passed in a magnetic field or without the latter (control experiments). The swollen cellulose was separated from the alkali at a certain time by pouring the suspension into a Buchner funnel, with the liquid run off into a vessel over a period of 30 sec, after which the swollen cellulose was squeezed and the extracted solution was mixed with the liquid that had passed through the funnel, or else no squeezing was employed. Then the solution was examined for hemicellulose. The mass balance was used to calculate the weight % hemicellulose extracted by diffusion and by squeezing.

Three series of control tests were done.

1. Extraction with a given bath modulus, given time, and specified initial caustic soda solution temperature. These runs were done in a glass vessel by the above method at 52-55°C.

2. In addition to the above, a laboratory stirrer provided vigorous flow in the system. The speed of the stirrer was always constant.

3. Experiments in the coaxial cylinder in an electric field with or without mixing.

The temperature in the coaxial cylinder was determined at half the distance between the walls. Repeated measurements at different times for a steady current of 20 A and a constant volume of $3 \cdot 10^{-4}$ m^3 for the caustic soda solution showed that the temperatures were extremely similar (difference not more than 2°C) for a given bath modulus with the external magnetic field and without it.

The caustic soda concentration c (about 227 g/liter) and the shape of the cellulose particles (rectangular, 10 × 10 mm) were kept constant in all cases.

Table 2 shows the field distribution and the current density and electromagnetic-field density for a liquid volume of $3 \cdot 10^{-4}$ m^3 and current of 20 A.

The electromagnetic forces in the cylinder were directed along the wall, and this results in rotation for bath moduli in excess of 15, whereas at moduli of 10 or less the cellulose swells and the electromagnetic forces cause the liquid to circulate between the particles. This circulation became less vigorous as the modulus was reduced.

The times used in extracting the hemicellulose were 120, 240, and 360 sec, with the bath modulus varying in the range from 20 to 6, and the extent of the swelling (ratio of the weight after squeezing to the weight of the dry residue) being 2.9-2.95 or 3.35-3.5; in addition, experiments were performed without squeezing.

Figures 2 and 3 show the results for hemicellulose extraction as kinetic curves derived from 5 or 6 analyses.

The results give the following conclusions.

1. Hemicellulose is extracted appreciably more rapidly in crossed electric and magnetic fields than it is in an electric field with vigorous stirring or in an electric field alone, as well as in runs with ordinary stirring or without stirring.

2. The rate of extraction in crossed fields is dependent on the bath modulus, i.e., on the degree of swelling in the cellulose.

3. The extraction in an electric field is somewhat more rapid than that under ordinary conditions.

NOTATION

j_l	is the current density in liquid;
j_p	is the current density inside particles;
c	is the concentration in liquid;
c_0	is the concentration in particles;
t	is the time;
$D_1 = mD$	is the mass-conduction factor [17];
D	is the diffusion coefficient;
m	is the porosity;
$D_c = D(m/m_v)$	is the concentration-conduction factor [17];
m_v	is the volumetric porosity;
x	is the coordinate;
$s = 2.46$	is the design factor (for a film);
δ	is the film half-thickness.

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RELATIVE DIFFUSION RESISTANCE IN DRYING WHEAT

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An apparatus is described for examining various methods of convective drying.

Convective drying of moist grain under optimal conditions retains all the technological and other features, and sometimes can even improve them.

Proper organization of the drying requires ordered movement of the water toward the surface of the particles without excessive depth of the evaporation zone and temperatures below the upper limit [1-3].

The diffusion rate within the grain is dependent on the form of water binding, the diffusion resistance, and the working conditions.

The relative diffusion resistance can [4, 5] be determined for any instant as the ratio of the drying rate in the constant-rate period (drying at the surface) to the drying rate in the second period when the outward diffusion rate is less than the surface evaporation rate, i.e., the dry layer increases the resistance.

Drying is accompanied by molecular diffusion and by molar diffusion [6]; therefore, by diffusion here we mean the overall process.

A laboratory equipment has been built [7] that enables one to perform tests with the grain layer in various states and with the temperature and speed of the drying agent adjustable over wide ranges (Fig. 1).

If the drying curve is known (Fig. 2), then the relative diffusion resistance R can be derived from

$$R = \frac{\mathrm{tg}\,\alpha}{\mathrm{tg}\,\varkappa} = \frac{N_{\mathrm{I}}}{(dW^c/d\tau)_{\mathrm{II}}}. \qquad (1)$$

This R indicates the reduction factor for the diffusion rate in the material relative to the rate in a layer of air at the same pressure and temperature. The drying curves and drying rate (Fig. 2) give R as a function of water content W^c (Fig. 3), which can be approximated as a power law:

$$R = \frac{A}{(W^c - W^c_e)^{\alpha}} + \gamma. \qquad (2)$$

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