

## DIFFUSION OF WATER THROUGH CERAMIC MIX IN ALTERNATING ELECTRIC FIELD

### Part II — Method of electric resistance drying under quasistationary conditions

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*The paper deals with the determination of the diffusion coefficient of water and its temperature dependence in an open system during the drying of a saturated porcelain mix with an inner electric heat source. The method is based on establishing the time dependence of the moisture content in the body and of the moisture profile under quasistationary conditions. In an open system, the effect of an alternating electric current promotes diffusion of water through saturated porcelain mix.*

### INTRODUCTION

Using the diffusion pair method with an inner electric heat source it was found in Part I that an alternating electric current speeds up diffusion of water in saturated porcelain mix [1]. Over the entire temperature interval studied, the diffusion coefficients were higher than those in a saturated porcelain mix free of an electric field. This finding was obtained with a closed system which did not allow for water transfer to the environment. The system consisted of two water-saturated bodies with different moisture contents, which constituted a saturated boundary over the area of contact. The effect of electric field on water transfer through a saturated ceramic mix established can be verified by creating an open system. As a result of passing the water to the environment, transfer of water in an open system is accelerated by capillary barodiffusion.

For a binary isotropic mix of incompressible components and a diffusion coefficient independent of moisture content, the moisture balance has the following form [2]:

$$\partial_t C = D_{\text{ef}} \operatorname{div} \operatorname{grad} C, \quad (1)$$

where  $\partial_t C$  is the differential of moisture content  $C$  by volume in terms of time,  $D_{\text{ef}}$  is the effective diffusion coefficient including the effect of capillary barodiffusion. The bulk diffusion flux of moisture  $\mathbf{h}$  is given by the equation

$$\mathbf{h} = -D_{\text{ef}} \operatorname{grad} C, \quad (2)$$

while it holds for bulk  $\mathbf{h}$  and the mass diffusion flux of moisture  $\mathbf{J}$  that

$$\mathbf{h} = \varrho v_1 v_2 \mathbf{J}, \quad (3)$$

where  $\varrho$  is the density of the mix,  $v_1$  and  $v_2$  are the partial specific volumes of components 1 and 2.

The behaviour of a water-saturated porcelain mix in an electric field approaches that of an insulant. In order to verify the effect of an electric field on water transfer in a saturated ceramic mix with an unsaturated boundary it is therefore impossible

to use the diffusion pair method employing a water-saturated body and an unsaturated one. However, an unsaturated surface arises in the course of drying of ceramic bodies.

The present study had the aim to work out a method for determining the diffusion coefficient of water holding for a ceramic body dried by an inner electric heat source, and to establish the effect of an electric field on water diffusion in a saturated porcelain mix exchanging moisture with the environment.

#### THE METHOD OF ELECTRIC RESISTANCE DRYING UNDER QUASISTATIONARY CONDITIONS

Determination of the diffusion coefficient of water in an open system with an electric field can be realized when drying a ceramic body by electric resistance under quasistationary conditions. Such conditions are characterized by a constant change in moisture content  $\partial_t C = \text{const}$ , a constant body temperature  $T = \text{const}$ , and for  $D \neq D(C)$  by a constant surface diffusion flux  $b = \text{const}$ . Under quasistationary conditions, the amount of water transferred by diffusion flux to the body surface is equal to the surface flux of water into the environment, i.e. the rate of drying. The suggested method of electric resistance drying under quasistationary conditions, during which the diffusion is unidirectional, is based on determining the dependence of moisture content on time and of the moisture profile in the body in quasistationary state. According to Fig. 1, for the drying of a plate  $2L$  in thickness from both sides under quasistationary conditions, equation (1) will have the form

$$\partial_t C = D_{\text{ef}} \partial_x^2 C = \text{const}, \quad (4)$$

where  $D_{\text{ef}}$  is the diffusion coefficient including the effect of capillary barodiffusion. The drying of a plate  $2L$  in thickness from both sides corresponds to the drying of a plate  $L$  in thickness from one side only.

On resolving equation (4) for the conditions

$$\begin{aligned} t > 0, \quad x = 0, \quad C = C_1 \\ x = L, \quad C = C_2 \end{aligned} \quad (5)$$

one obtains description of the moisture profile in the form

$$C(x) = \frac{\Delta C}{2 \Delta t D_{\text{ef}}} x^2 + \left( \frac{(C_2 - C_1)}{L} - \frac{\Delta C L}{2 \Delta t D_{\text{ef}}} \right) x + C_1. \quad (6)$$

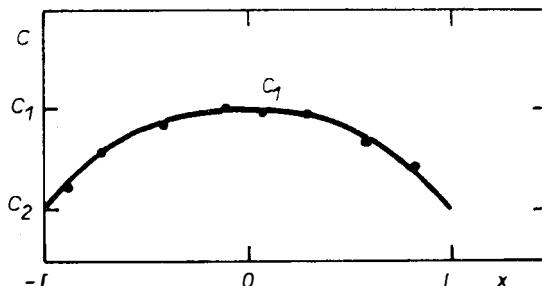


Fig. 1. Moisture profile in a plate during drying from both sides.

where  $\Delta C$  is the difference in moisture content  $\Delta C = C_A - C_B$  during time  $\Delta t$ . If equation (4) is resolved on the condition of moisture profile symmetry at  $x = 0$ , i.e. in the form

$$\begin{aligned} t > 0, \quad x = 0, \quad dC/dx = 0, \\ x = L \quad C = C_2, \end{aligned} \quad (7)$$

the moisture profile is described by the equation

$$C(x) = \frac{\Delta C}{2 \Delta t D_{\text{ef}}} x^2 + C_2 - \frac{\Delta C}{2 \Delta t D_{\text{ef}}} L^2. \quad (8)$$

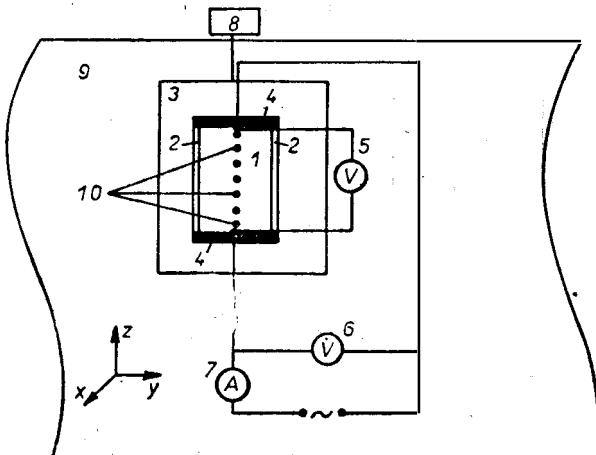


Fig. 2. Schematic diagram of electric resistance drying under quasistationary conditions; 1 — body, 2 — moisture proofing, 3 — thermal insulation, 4 — electrodes, 5, 6 — voltmeter, 7 — ammeter, 8 — balance, 9 — laboratory recycling drying oven, 10 — thermocouples.

Knowledge of  $\Delta C/\Delta t$  and  $C = C(x)$  for the drying of a body under quasistationary conditions allows  $D_{\text{ef}}$  to be calculated from equation (6) or (8). The experimental arrangement of the method is shown in Fig. 2. The body of prismatic shape with initial homogeneous moisture distribution is thermally insulated and moisture-proofed in directions  $y$  and  $z$ . Electrodes supply adjustable constant alternating voltage measured with a voltmeter. The current passing through the body is measured with an ammeter and the temperature field by a system of copper-constantan thermocouples. The insulated body with the electrodes is placed on a balance in a recycling drying oven provided with temperature, relative humidity and air flow rate controls. In the course of drying, the time dependence of body weight  $G = G(t)$ , electric current  $I = I(t)$  at constant voltage  $U$ , of temperature profiles  $T = T(t, x)$  were measured. Following attainment of quasistationary conditions of electric resistance drying, the body was cut up in direction  $x$  in order to determine the moisture profile  $C = C(x)$ , and the time dependence of mean absolute moisture content  $\bar{w}$  was expressed according to the time dependence of the weight losses.

## EXPERIMENTAL RESULTS

The moisture content distribution and the time dependence of moisture content during electric resistance drying under quasistationary conditions were measured at various mean body temperatures  $T$  over the temperature range  $T \in \langle 295 \text{ K}; 323 \text{ K} \rangle$ . Typical results of measuring  $\bar{w} = \bar{w}(t)$ ,  $\bar{T} = \bar{T}(t)$  and  $\bar{I} = \bar{I}(t)$  for bodies  $2L = 3 \cdot 10^{-2} \text{ m}$  in thickness and voltage  $U = 24.6 \text{ V}$  on the body are plotted in Fig. 3. The moisture profile  $C = C(x)$  in the body, determined at time  $t = 25$  minutes, is shown in Fig. 4. Similar relationships were established for other mean body temperatures.

On using for  $T = 317 \text{ K}$  the values  $C_1 = 0.4152 \text{ m}^3 \text{ m}^{-3}$ ,  $C_2 = 0.4002 \text{ m}^3 \text{ m}^{-3}$ ,  $\Delta C/\Delta t = -1.73 \cdot 10^{-5} \text{ m}^3 \text{ m}^{-3} \text{ s}^{-1}$ , it is possible to calculate from equation (6)

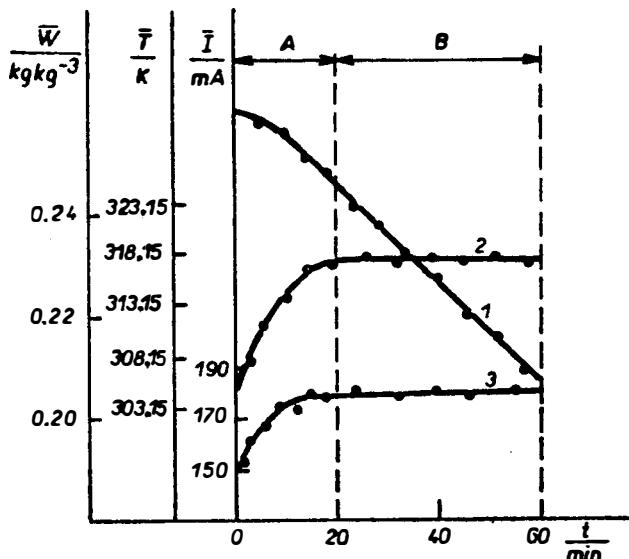


Fig. 3. The dependences measured during electric resistance drying of the body; A — heating through of the body, B — quasistationary conditions 1 —  $\bar{w} = \bar{w}(t)$ , 2 —  $\bar{T} = \bar{T}(t)$ , 3 —  $\bar{I} = \bar{I}(t)$ .

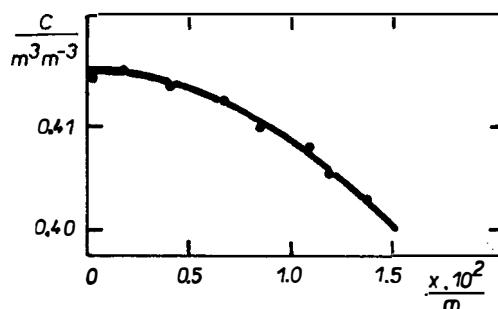


Fig. 4. Moisture profile in the body.

or (8) the value of the effective diffusion coefficient of water in ceramic mix in an electric field,  $D_{ef} = 1.1 \cdot 10^{-7} \text{ m}^2 \text{ s}^{-1}$ . The  $D_{ef}$  established at various mean temperatures are listed in Table I.

*Table I*  
Effective diffusion coefficient of water in a saturated  
ceramic mix in alternating electric field at various  
temperatures

$\frac{T}{K}$	295	310	317	323
$\frac{D_{ef} \cdot 10^7}{\text{m}^2 \text{ s}^{-1}}$	0.7	0.9	1.1	1.5

#### DISCUSSION AND CONCLUSION

On the basis of the results obtained it may be confirmed that the method of electric resistance drying under quasistationary conditions allows the diffusion coefficient of water in a saturated ceramic mix with an unsaturated surface under the effect of alternating electric field to be reliably determined.

The  $D_{ef}$  values obtained at the various temperatures were approximated by the equation

$$D_{ef} = (2.46 \cdot 10^{-4} \exp(-2425/T)) \quad \text{m}^2 \text{ s}^{-1} \quad (9)$$

which holds over the temperature interval  $T \in \langle 295; 323 \rangle \text{ K}$ .

Paper [3] was concerned with determining the temperature dependence of the diffusion coefficient of water in a saturated ceramic mix with an unsaturated surface, in the absence of an electric field, which had the form

$$D_{ef} = (3.93 \exp(-5645/T)) \quad \text{m}^2 \text{ s}^{-1}. \quad (10)$$

A comparison of equations (9) and (10) shown in Fig. 5 indicates that the presence of an alternating electric field accelerates diffusion of water through a saturated

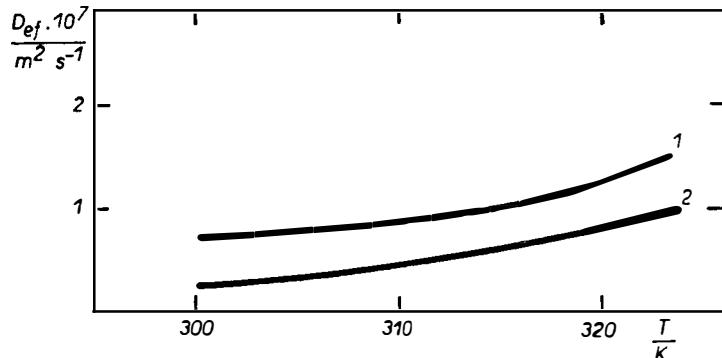


Fig. 5. Temperature dependence of the effective diffusion coefficient  $D_{ef}$ ; 1 — from equation (9), 2 — from equation (10).

porcelain mix with an unsaturated boundary. The same finding was obtained in Part I for a saturated mix with an unsaturated boundary [1].

An explanation of the effect of alternating electric current on the diffusion of water through a ceramic mix can be based on the hypothesis introduced in the elucidation of the differences in the temperature dependence of electric conductance of porcelain mixes in study [4]. It is assumed that the alternating electric field probably impairs the structure of lyospheres on the surface of the solid phase, ostensibly by the vibrating motion of the ions present, thus improving the mobility of water. An increase in the number of mobile water molecules resulting from the effect of the electric fields also corresponds to the higher value of  $D$  over the entire temperature interval. It may therefore be assumed that under the effect of electric current, the number of molecular layers of electrolyte adsorbed on the solid phase surface decreases; this phenomenon is associated with an expansion of capillaries and pores in the body and subsequently with increased bulk flux of the electrolyte through the mix.

#### References

- [1] Havrda J., Gregorová E., Oujíří F.: Silikáty 34, 97 (1990)
- [2] Slatterly J. C.: *Momentum, Energy and Mass Transfer in Continua*, New York, McGraw-Hill, 1972.
- [3] Havrda J., Oujíří F.: Silikáty 26, 203 (1982).
- [4] Havrda J., Gregorová E., Oujíří F.: Silikáty 34, 291 (1990).

### DIFÚZE VODY KERAMICKOU SMĚSÍ VE STŘÍDAVÉM ELEKTRICKÉM POLI

Část II. Metoda elektroodporového sušení v kvazistacionárním režimu

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V práci je ověřován vliv střídavého elektrického pole na přenos vody v nasycené keramické směsi s nenasyceným rozhraním. Je vypracována metoda stanovení difúzního koeficientu vody při sušení tělesa s vnitřním elektrickým zdrojem tepla. Metoda spočívá v určení závislosti vlhkosti tělesa na čase a vlhkostního profilu v tělese v kvazistacionárním režimu. V průběhu sušení jsou měřeny časové závislosti hmotnostních úbytků tělesa, elektrického proudu při konstantním napětí a teplotních profilů. Ze stanovených vlhkostních profilů je spočítán efektivní difúzní koeficient pro příslušnou střední teplotu a je vyjádřena teplotní závislost ve tvaru

$$D_{et} = (2,46 \cdot 10^{-4} \exp(-2425/T)) \text{ m}^2 \text{ s}^{-1}.$$

Porovnání s difúzním koeficientem vody nasycenou keramickou směsí s nenasyceným povrchem bez přítomnosti vnitřního elektrického zdroje tepla dokazuje, že přítomnost střídavého elektrického pole urychluje difúzi vody nasycenou porcelánovou směsí.

Obr. 1. Vlhkostní profil v desce při oboustranném sušení.

Obr. 2. Schéma metody elektroodporového sušení v kvazistacionárním režimu; 1 — těleso, 2 — vlhkostní izolace, 3 — tepelná izolace, 4 — elektrody, 5, 6 — voltmetr, 7 — ampérmetr, 8 — váhy, 9 — laboratorní cirkulační sušárna, 10 — termoflánky.

Obr. 3. Měřené závislosti při elektroodporovém sušení tělesa; A — prohřev tělesa; B — kvazistacionární režim 1 —  $\bar{w} = \bar{w}(t)$ , 2 —  $T = T(t)$ , 3 —  $I = I(t)$ .

Obr. 4. Vlhkostní profil v tělese.

Obr. 5. Teplotní závislost efektivního difúzního koeficientu  $D_{et}$ ; 1 — ze vztahu (9), 2 — ze vztahu (10).

ДИФФУЗИЯ ВОДЫ ЧЕРЕЗ КЕРАМИЧЕСКУЮ СМЕСЬ  
В ПЕРЕМЕННОМ ЭЛЕКТРИЧЕСКОМ ПОЛЕ

II. Метод электросопротивительной сушки в квазистационарном режиме

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В приводимой работе проверяется влияние переменного электрического поля на передачу воды в насыщенной керамической смеси с ненасыщенным пределом. Авторами разрабатывается метод определения коэффициента диффузии воды при сушке тела с внутренним электрическим источником тепла. Метод основывается на определении зависимости влажности тела от времени и профиля влажности в теле в квазистационарном режиме. Во время сушки измеряются временные зависимости убыли массы тела, электрического тока при постоянном напряжении и температурных профилях. На основании установленных профилей влажности рассчитывается эффективный коэффициент диффузии относительно соответствующей средней температуры и выражается температурная зависимость в виде:

$$D_{\text{ef}} = (2,46 \cdot 10^{-4} \exp(-2425/T)) \text{ m}^2\text{s}^{-1}$$

Сопоставление с коэффициентом диффузии через насыщенную керамическую смесь с насыщенной поверхностью в отсутствии внутреннего электрического источника тепла показывает, что присутствие переменного электрического поля ускоряет диффузию через насыщенную фарфоровую смесь.

*Рис. 1. Профиль влажности в пакете при двусторонней сушке.*

*Рис. 2. Схема метода электросопротивительной сушки в квазистационарном режиме; 1 — тело, 2 — изоляция влажности, 3 — термоизоляция, 4 — электроды, 5, 6 — вольтметр, 7 — амперметр, 8 — весы, 9 — лабораторная циркуляционная сушилка, 10 — термоэлементы.*

*Рис. 3. Измеряемые зависимости при электросопротивительной сушке тела; A — нагрев тела, B — квазистационарный режим 1 —  $\bar{w} = \bar{w}(t)$ , 2 —  $T = T(t)$ , 3 —  $I = I(t)$ .*

*Рис. 4. Профиль влажности в т.ч.*

*Рис. 5. Температурная зависимость эффективного коэффициента диффузии  $D_{\text{ef}}$ : 1 — из соотношения (9), 2 — из соотношения (10).*

*Recenze knih*

**JOACHIM LANGE: ROHSTOFFE DER GLASINDUSTRIE** (Suroviny pro sklářský průmysl). 2. přepracované a rozšířené vydání. VEB Deutscher Verlag für Grundstoffindustrie Lipsko NDR 1988, 196 str., 99 tab., 43 obr.

Po 8 letech od 1. vydání máme možnost se seznámit s 2. přepracovaným a rozšířeným vydáním učebnice vhodné pro výuku na vysokých školách zabývajících se přípravou odborných pracovníků pro sklářské odvětví.

Učebnice podává ucelený přehled o nejdůležitějších sklářských surovinách, jejich vlastnostech a použití. Je rozdělena do 6 kapitol.

Kapitola 1 je věnována všeobecným úvahám o sklářských surovinách, jejich úloze při tvorbě skla a jejich vlivu na vlastnosti skla. Kapitola je doplněna příklady praktických výpočtů, např. přepočtu molárních procent na hmotnostní a naopak, výpočtu hustoty, specifického tepla, tepelné vodivosti, modulu elasticity, povrchového napětí, dielektrické konstanty, viskozity atd. Kapitola 2 obsáhle pojednává o jednotlivých sklářských surovinách, jejich působení na tvorbu skla, nalezištích, technologických a kvalitativních kritériích. Kapitola 3 se zabývá chemicko-technickými přepočty, stechiometrií, odlišnostmi výpočtu složení skel obsahujících fluor, přesnosti výpočtů aj. Obsah kapitoly 4 tvoří ve srovnání s 1. vydáním samostatnou část, ve které se řeší problémy vzniklé