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THE EFFECT OF TEMPERATURE ON TRANSFER OF WATER IN A SATURATED CERAMIC BODY

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Water transfer in a saturated ceramic body at various temperatures was studied in the systems where the boundary between the water-saturated body and environment was either saturated or unsaturated. The diffusion pair (couple) *method and that of drying under quasistationary conditions were employed in the study. The temperature dependence of the diffusion coefficient was expressed for these systems.*

INTRODUCTION

Water transfer in a saturated ceramic mix, i. e. in a mixture of the ceramic material and water, can be regarded as diffusion in a binary mixture of two incompressible components [1]. This conception allowed to determine the effect of the state of the surface, or that of the boundary of a saturated ceramic body on the mechanism of water transfer, thus elucidating the difference in order of magnitude between the values of diffusion coefficients measured by the diffusion pair method and by methods based on drying or removal of water by a gypsum block [2], [3]. The boundaries may be satured or unsaturated. Saturated are insulated boundaries or boundaries between two saturated bodies. Unsaturated are boundaries of a saturated body with an unsaturated body or ambient atmosphere. The effect of saturation or unsaturation of the boundary on the diffusion coefficient value has been reliably proved by experiment at one temperature. In the case of the saturated boundary the diffusion coefficient is lower by one order of magnitude than that in a saturated body with an unsaturated boundary. Under isothermal conditions the diffusion coefficient in a saturated body with a saturated boundary corresponds to water transfer resulting solely from the effect of the moisture gradient. In the case of an unsaturated boundary the diffusion coefficient can be regarded as an effective magnitude related to water transfer resulting from a moisture gradient and from capillary barodiffusion, that is capillary suction in the menisci as the unsaturated boundary. It has also been found that the diffusion coefficient value established by the diffusion pair method with an unsaturated boundary is the same as its value determined by the quasistationary drying method at the same temperature, and moreover, that the independence of the diffusion coefficient on moisture content in a saturated ceramic body is not affected by the state of its boundary. Water transfer in a saturated ceramic mix can then be described when knowing the temperature dependence of the diffusion coefficient [4], [5].

The present work was therefore aimed at determining the temperature dependence of the diffusion coefficient in a saturated body with both saturated and unsaturated boundaries, and to establish whether the data obtained at one temperature are also valid within a wider temperature range. In order to obtain this information, the temperature dependence of the diffusion coefficient was measured at the following three experimental arrangements:

(1a) diffusion pair composed of two saturated bodies of different moisture contents — saturated boundary, (1b) diffusion pair composed of one saturated body and the other unsaturated body — unsaturated boundary,

(2) saturated ceramic body with a free surface, on which the water is evaporated at a constant rate, i.e. quasistationary drying — unsaturated boundary.

THEORY

When the structure of the solid component is homogeneous and constant, both components are incompressible and the diffusion coefficient independent of moisture, then the following relationship holds under isothermal conditions for one-dimensional diffusion for that part of the diffusion pair which has the higher moisture content [6]:

$$Y = \operatorname{erf}\ (1/2\, x\, (D\tau)^{-1/2}), \tag{1}$$

where $Y = (C - C_s) / (C_2 - C_s)$, C_s being the moisture content by volume at the boundary of the two parts of the diffusion pair, and C_2 is the initial moisture content by volume.

Bilateral quasistationary drying of a plate results to establishment of a parabolic moisture distribution and the diffusion coefficient can then be calculated from the equation [3], [5]:

$$D = J_s L / 4\, \Delta C, \tag{2}$$

where J_s is the volume moisture flow through the plate surface, L is the plate thickness, $\Delta C = C_c - C_p$, where C_c and C_p are moisture contents by volume at the centre and at the plate surface respectively.

THE MEASURING PROCEDURE

The water transfer was investigated in a saturated ceramic mix for electrotechnical porcelain with an evelated content of $\alpha - Al_2O_3$. The measurements were carried out on prismatic elements 3×3 cm in cross section and 10 cm in length, prepared by drawing a mix of 26% moisture content on a vacuum auger. Some of the specimens were insulated immediately after forming and kept for 48 hours in a water-vapour saturated medium to achieve uniform moisture distribution throughout the specimen body [7]. From some other specimens, 4% of moisture were removed by drying, the specimens were then insulated and stored in the same way as in the previous case. The remaining specimens were dried to zero moisture content and insulated.

In the determination of the diffusion coefficient by the diffusion pair method in the instance of saturated boundary (1a) the diffusion pair was composed of two saturated bodies of different moisture contents. In the case of unsaturated boundary (1b) the diffusion pair was composed of a body with the initial moisture content and a body dried to zero moisture content. The experimental procedure was the same for both arrangements. Both insulated parts of the pair were separately heated at working temperature T for a period of 40 minutes. After completed heating, the insulation was removed from one base of both specimens, a diffusion pair composed by joining the bodies and the neighbourhood was insulated. The diffusion pair was kept at the constant temperature T for a period of time τ. Then followed cooling of the pair down to $T = 278$ K. The insulation was removed from the cooled pair and the part of the pair having the higher moisture content was cut into 2 mm strips to determine their moisture content. The diffusion coefficient was determined from moisture distribution using equation (1). The same procedure was employed for all the working temperatures.

In the determination of the diffusion coefficient by the quasistationary drying method (2), insulation of both bases was removed from the saturated specimen in the length of 3 cm, and the specimen was placed in a laboratory recycling drying oven [8] with its bases parallel with the direction of the flowing air. In all the experiments the air temperature was 318 K and the rate of air flow was 1.7 m s^{-1}. Under the quasistationary conditions the specimen temperature corresponds to the temperature of adiabatically saturated air. The various specimen temperatures were therefore achieved by chainging the relative humidity of the medium in the range from 30 to 80 %. Under the quasistationary conditions, the volume flow J_s and the moisture distribution in the specimen were determined for the expression of ΔC. The diffusion coefficient was calculated according to equation (2).

RESULTS

For the arrangement employed (1a), (1b), (2) the moisture distribution in the saturated body at each temperature was measured at least twice. The typical moisture profiles are shown in Fig. 1. The mean diffusion coefficient values for various temperatures are plotted in Fig. 2.

DISCUSSION

The temperature dependence of diffusion coefficients in the temperature range measured was approximated for all the arrangements by the following expression:

$$D = D_0 \exp(-B/T), \tag{3}$$

where B is the characteristic temperature of the process and D_0 is a constant. The mean quadratic error

$$\delta_k = \left[\sum_{i=1}^{n} (D_i - D_{iv})^2/(n-1) \right]^{1/2},$$

where D_{iv} is the diffusion coefficient value calculated according to (3). The values of the constants in equation (3) for the individual arrangements are as follows:

$$\text{(1a)}\quad D_0 = 5.52 \times 10^{11}\ \mathrm{m^2\ s^{-1}},\quad B = 14\,484\ \mathrm{K},\quad \delta_k = 1.1 \times 10^{-17}\ \mathrm{m^2\ s^{-1}}, \tag{4}$$

$$\text{(1b)}\quad D_0 = 3.93\ \mathrm{m^2\ s^{-1}},\quad B = 5\,645\ \mathrm{K},\quad \delta_k = 3.7 \times 10^{-17}\ \mathrm{m^2\ s^{-1}}, \tag{5}$$

$$\text{(2)}\quad D_0 = 71.3\ \mathrm{m^2\ s^{-1}},\quad B = 6\,520\ \mathrm{K},\quad \delta_k = 4.2 \times 10^{-18}\ \mathrm{m^2\ s^{-1}}. \tag{6}$$

The results of this study are in a close agreement with the findings mentioned in the introduction. Fig. 2 for arrangement (1a) and (1b) implies that acceleration of water transfer in a saturated body with an unsaturated boundary due to barodiffusion occurs throughout the entire temperature range measured. At the lowest temperature employed (278 K) the diffusion coefficient differs by about 2 orders of magnitude. This difference decreases with increasing temperature, until at 333 K the ratio of the two diffusion coefficients amounts to 2.3. In the case (1b), the B is 2.56 times lower than with the saturated body with the saturated boundary. This difference can be explained by a small dependence of surface tension on temperature. Fig. 2 for arrangement (1b) and (2) indicates that the diffusion coefficient values established by the two methods at various temperatures are in a satisfactory

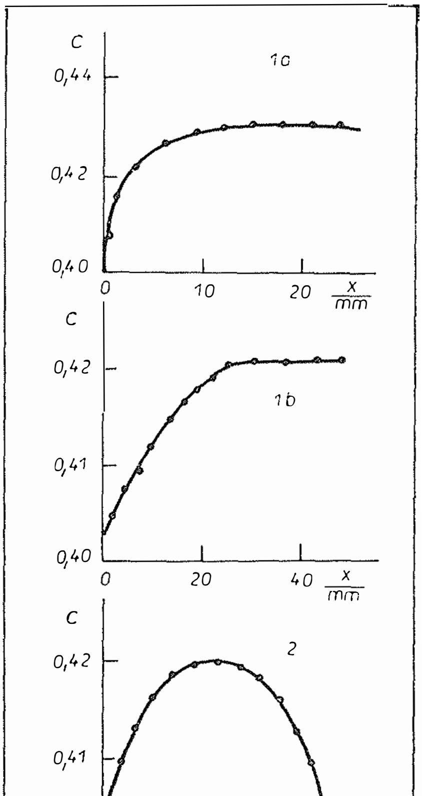

Fig. 1. Moisture profile in a saturated body for arrangements (1a), (1b), (2). (1a): $T = 290$ K, $\tau = 24$ hrs, (1b): $T = 293$ K, $\tau = 4$ hrs, (2): $T = 314.2$ K, $\tau = 1$ hrs.

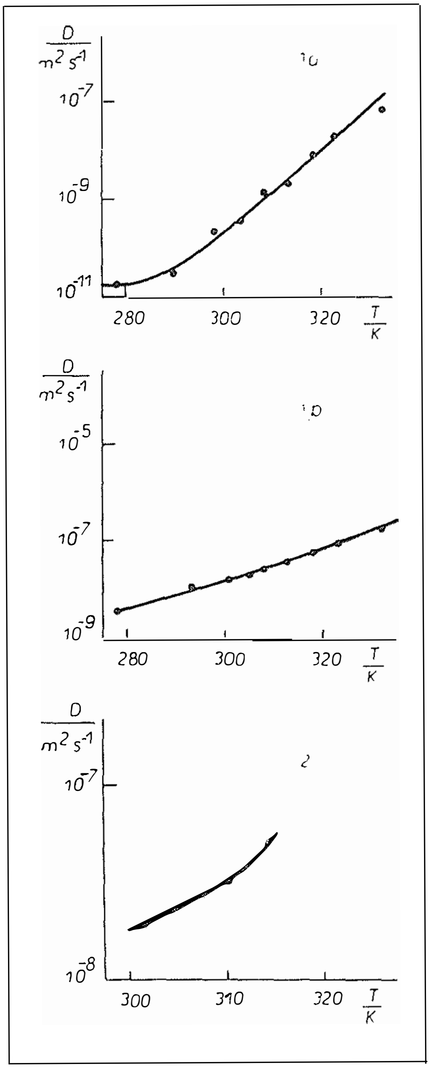

Fig. 2. Diffusion coefficient vs. temperature for arrangements (1a), (1b), (2).

mutual agreement. This means that when a saturated body has an unsaturated boundary or surface, the temperature dependence of the diffusion coefficient is virtually the same ragardless of whether the unsaturated boundary is due to the contact of the saturated body with a dried body or with ambient atmosphere.

CONCLUSION

1. The temperature dependence of the diffusion coefficient for a given water-saturated ceramic mix for the temperature range measured is described by equation (3) with the values of constants (4) in the case (1a) of the diffusion pair method with a saturated boundary, with values of constant (5) in the case (1b) of the diffusion pair method with an unsaturated boundary, and with values of constants (6) in the case (2) of the quasistationary drying method.

2. In the temperature range measured, the diffusion coefficient values in the saturated body with a saturated boundary are lower than in the instance of the saturated body with an unsaturated boundary.

3. The method of the diffusion pair composed of a saturated and dried body is a model of water transfer in a saturated body under quasistationary drying conditions in the temperature range of 302.5 to 314.2 K.

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VLIV TEPLOTY NA PŘENOS VODY V NASYCENÉM KERAMICKÉM TĚLESE

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Teplotní závislost difúzního koeficientu vody v nasyceném keramickém tělese byla určena (1) metodou difúzního páru a (2) metodou kvazistacionárního sušení. Difúzní páry byly sestaveny (1a) ze dvou nasycených těles nebo (1b) z jednoho tělesa nasyceného a druhého nenasyceného. Difúzní koeficient při sušení byl určován (2) z rychlosti sušení. Bylo zjištěno, že hodnoty difúzních koeficientů v proměřeném teplotním intervalu metodami (1b) a (2) jsou prakticky stejné a jsou vyšší než hodnoty difúzních koeficientů stanovené metodou (1a). Teplotní závislost difúzního koeficientu pro sledovanou směs technického porcelánu ve zvoleném intervalu teplot je popsána vztahem:

$$D = D_0 \exp(-B/T),$$

s hodnotami konstant v případě:

(1a) $D_0 = 5{,}52 \cdot 10^{11}\ \mathrm{m^2 s^{-1}}$, $B = 14\,484\ \mathrm{K}$, $\langle 278-333\ \mathrm{K}\rangle$,
(1b) $D_0 = 3{,}93\ \mathrm{m^2 s^{-1}}$, $B = 5645\ \mathrm{K}$, $\langle 278-333\ \mathrm{K}\rangle$,
(2) $D_0 = 71{,}3\ \mathrm{m^2 s^{-1}}$, $B = 6520\ \mathrm{K}$, $\langle 301-314\ \mathrm{K}\rangle$.

Obr. 1. Vlhkostní profil v nasyceném tělese pro uspořádání (1a), (1b), (2).
(1a): $T = 290$ K, $\tau = 24$ h, (1b): $T = 293$ K, $\tau = 4$ h, (2): $T = 314{,}2$ K, $\tau = 1$ h.
Obr. 2. Závislost difúzního koeficientu na teplotě pro uspořádání (1a), (1b), (2).

ВЛИЯНИЕ ТЕМПЕРАТУРЫ НА ПЕРЕНОС ВОДЫ В НАСЫЩЕННОМ КЕРАМИЧЕСКОМ ТЕЛЕ

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Температурную зависимость коэффициента диффузии воды в насыщенном керамическом теле определяли методом диффузионной пары (1) и методом квазистационарной сушки (2). Диффузионные пары состояли или из двух насыщенных тел (1a) или из одного насыщенного и второго ненасыщенного тел (1b). Коэффициент диффузии при сушке определяли на основании скорости сушки (2). Установили, что величины коэффициентов диффузии в измеряемом интервале температуры с помощью методов (1b) и (2) практически одинаковы и достигают более высокой величины по сравнению с величинами коэффициентов диффузии, установленных с помощью метода (1a). Температурная зависимость коэффициента диффузии для исследуемой смеси технического фарфора в подобранном интервале температур описывается отношением:

$$D = D_0 \exp(-B/T).$$

с величинами констант в случае:

(1a) $D_0 = 5{,}52 \,.\, 10^{11}$ м^{2}с$^{-1}$, $B = 14\,484$ K, ⟨278—333 K⟩,
(1b) $D_0 = 3{,}93$ м^{2}с$^{-1}$, $B = 5\,645$ K, ⟨278—333 K⟩,
(2) $D_0 = 71{,}3$ м^{2}с$^{-1}$, $B = 6\,520$ K, ⟨301—314 K⟩.

Рис. 1. Профиль влажности в насыщенном теле в случае упорядочения (1a), (1b), (2). (1a): $T = 290$ K, $\tau = 24$ часов, (1b): $T = 293$ K, $\tau = 4$ часа, (2): $T = 314{,}2$ K, $\tau = 1$ час.

Рис. 2. Зависимость коэффициента диффузии от температуры в случае упорядочения (1a), (1b), (2).