THE EFFECT OF TEMPERATURE GRADIENT ON WATER TRANSFER IN A SATURATED CERAMIC MIX

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Received 8. 10. 1981

A method has been suggested for studying water transfer in saturated ceramic mix resulting from temperature gradient, and conditions for reliable determination of the thermodiffusion coefficient have been established. The thermodiffusion coefficient value was determined experimentally for one mean temperature; it was found that at small temperature gradients the effect of thermodiffusion on water transfer in a saturated ceramic mix, having a saturated boundary, can be neglected.

INTRODUCTION

In a saturated ceramic mix, i.e. a mixture of ceramic material and water, the transfer of water may be regarded as diffusion in a binary mixture of two incompressible components [1]. If the water transfer proceeds under isothermally isobaric conditions, it is due to a concentration gradient. There are also situations when the transfer is caused by both a concentration gradient and a temperature gradient. An example is provided by the maturing of ceramic mixes. The significance of temperature gradient in water transfer in a saturated ceramic body has not so far been determined explicitly. In the given case, the volume moisture flow depends on the direction and size of the two gradients. A quantitative description of the transfer would require knowledge of both the temperature and concentration dependences of the diffusion coefficient, and knowledge of the termodiffusion coefficient. The present study had the objective to work out a method and to determine conditions for reliable measurements of thermodiffusion of water, and to establish its effect on water transfer in a saturated ceramic mix. The required information was obtained experimentally on a saturated ceramic mix with a saturated boundary [2]. The temperature dependence of the diffusion coefficient for this system is known, and the situation is not complicated by capillary barodiffusion [2], [3].

THEORY

When considering a homogeneous and constant system free from external forces and when neglecting the viscous flow phenomena, then for incompressible components the moisture balance has the form [4]:

$$\partial C/\partial \tau = -\mathrm{div}\,\boldsymbol{h} \tag{1}$$

where C is moisture volume content, that is the volume of water per unit volume of mix, τ is time and $\boldsymbol{h}$ is moisture diffusion flow. In a situation when only the moisture and temperature gradient are involved, the diffusion flow is described by the equation:

$$\boldsymbol{h} = \boldsymbol{f}(\mathrm{grad}\ C,\ \mathrm{grad}\ T). \tag{2}$$

If function f is linear and isotropic, equation (2) attains the form:

$$h = -D \operatorname{grad} C - D_T \operatorname{grad} \ln T, \qquad (3)$$

where D is the diffusion coefficient and D_T is the thermodiffusion coefficient. By substituting equation (3) into the moisture content balance (1), one obtains a differential equation for moisture fields:

$$\partial C/\partial \tau = \operatorname{div} (D \operatorname{grad} C + D_T \operatorname{grad} \ln T). \qquad (4)$$

The time development of the temperature profile in a saturated ceramic body is described by the Fourier—Kirchhoff equation [5] when the Dufour's effect is neglected:

$$c_p \varrho \, \partial T/\partial \tau = \operatorname{div} (\lambda \operatorname{grad} T), \qquad (5)$$

where $c_p \varrho$ is thermal capacity of unit volume and λ is thermal conductivity of the medium. Solution of equations (4) and (5) yields the time development of the moisture field in a saturated ceramic body.

Determination of the thermodiffusion coefficient by the two heat sources method

On assuming that in a saturated body with initial homogeneous and constant moisture distribution (grad $C = 0$) there is established, within period τ, a linear and constant temperature profile described by equation (5) adjusted for an equalized state, a moisture gradient is developed by the effect of the temperature gradient. The process results in attainment of a steady state, when $\overline{h} = 0$ and equation (3) for the one-dimensional problem has the form:

$$D \, dC/dx = -D_T(dT/T \, dx), \qquad (6)$$

where x is a coordinate. The two-thermal sources method (further on **TTSM**), in which thermodiffusion is one-dimensional, is therefore based on creation of a constant linear temperature profile, and on determining the moisture profile established on attainment of a steady state. For a rough estimate of the time of equalization of the process it holds [5]:

$$\tau' \approx L^2/D, \qquad (7)$$

where L is body thickness in the temperature gradient direction.

EXPERIMENTAL

Measurement by the two thermal sources method

The measurements were performed on prismatic bodies $1.2 \, \text{cm} \times 4 \, \text{cm}$ in cross section and 10 cm in length, prepared by extrusion of ceramic mix for electrotechnical porcelain with a raised $\alpha-\text{Al}_2\text{O}_3$ content using a vacuum auger. To prevent moisture exchange with the environment, the body surface was insulated and for 48 hours the body was placed in a water-saturated medium to achieve uniform moisture distribution throughout the body volume. The experimental arrangement complied with the following conditions:

$$\tau = 0 \; x = 0 \; C = C_0 \; T = T_1$$
$$T_1 > T_2, \qquad (8)$$
$$x = L \; C = C_0 \; T = T_2$$

$$\tau = \tau' \ x = 0 \ C = C_1 \ T = T_1$$
$$T_1 > T_2. \tag{9}$$
$$x = L \ C = C_2 \ T = T_2$$

From the temperature dependence of D determined by the diffusion couple method with saturated boundary [3]:

$$D = 5.52 \times 10^{11} \exp(-14\,484/T) \cdot m^2\,s^{-1}, \tag{10}$$

an estimate of time was carried out according to (7). For $L = 1.2 \times 10^{-2}$ m and the mean temperature $\bar{T} = 319.6$ K, $\tau' = 4$ hrs. It was found experimentally that a period of 7 hours ensures attainment of a steady state. An isolated saturated ceramic body was kept for 7 hours between two thermal sources of different constant temperature where the body surface temperature was $T_1 = 336.3$ K and $T_2 = 303$ K. Then followed cooling of the body down to $T = 278$ K, removal of insulation and cutting into 1.2 mm slices for moisture determination. At the given source temperatures the temperature profile in the body was measured by means of copper-konstantan thermocouples. The moisture profile was measured ten times and the temperature profile twice. The corresponding gradients were evaluated from the temperature and moisture profiles, and the D_T values calculated according to (6) were treated by the Student's test.
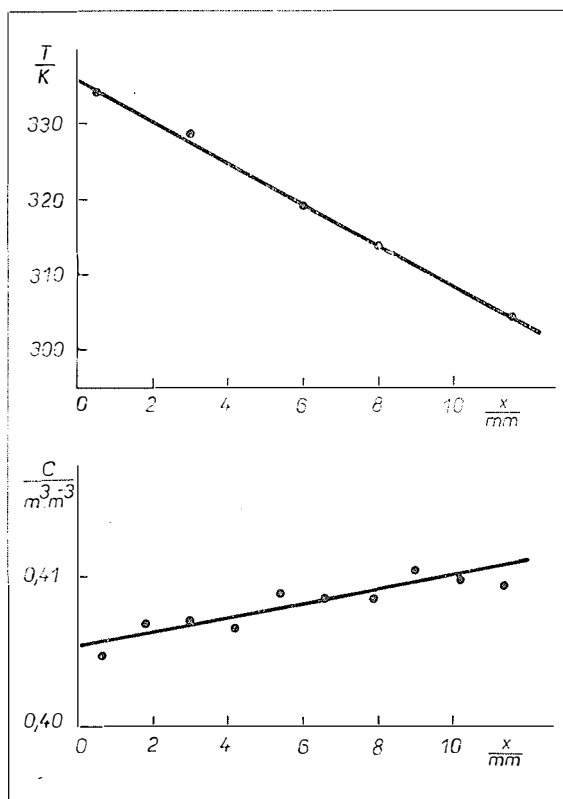

Fig. 1. Temperature and moisture profile in the body at $\bar{T} = 319.6$ K.

The results

A typical temperature and moisture profile in a body determined by the TTSM is shown in **Fig. 1.** The temperature and moisture profiles were approximated by a linear dependence. The lowest correlation coefficient value was that for temperature profile, 0.96, while that for the moisture profile varied form 0.7 to 0.98, with a mean at 0.86. The evaluated D_T for $T = 319.6 \, K$ are listed in Table I.

Table I

The values of thermodiffusion coefficients

Measurement No.	1	2	3	4	5	6	7	8	9	10
$D_T \cdot 10^{10}/m^2s^{-1}$	4.6	3.5	6.1	7.4	4.6	6.8	6.1	3.8	7.2	6.6
$(D_T \pm \delta) \, m^2s^{-1}$	$(6 \pm 1) \times 10^{-11}$									

*) $(\bar{D}_T \pm \delta)$ is the mean value including the error of results

The following conditions for reliable determination of D_T have been derived from the experimental work:
— reproducible preparation of bodies with homogeneous and constant initial moisture distribution,
— a constant and reproducible temperature gradient,
— satisfactory quality of the insulating layer,
— attainment of a stedy state,
— rapid cooling down of the body before cutting it up.

DISCUSSION

The assumption of a constant linear temperature distribution in a saturated ceramic body in a steady temperature state $(\partial T/\partial \tau = 0, \, d^2T/dx^2 = 0)$ is met by the temperature profile in the form:

$$T = ((T_2 - T_1) \cdot x/L) + T_1. \tag{11}$$

If the dependence D and D_T on T is neglected and both values refer to $T = (T_1 + T_2)/2$ then for steady state $(\bar{h} = 0)$ follows the constant moisture profile by solving (6) in the form:

$$C = ((C_2 - C_1) \cdot x/L) + C_1. \tag{12}$$

The temperature and moisture profiles established experimentally are in a satisfactory agreement with relationships (11) and (12). The $\bar{D}_T$ values for $T = 319.6 \, K$ may be considered as reliably determined with respect to the measurement reproducibility involved. There remains the question of the share of thermodiffusion on the water transfer in a saturated ceramic body with a saturated boundary. In a water-saturated body the moisture gradient value is approx. $dC/dx = 0.5 \, m^{-1}$ and that of the temperature gradient $dT/dx = 100 \, K \, m^{-1}$ [6]. For $T = 319.6 \, K$, the value $\bar{D}_T = 6 \times 10^{-10} \, m^2 \, s^{-1}$ and $D = 1.2 \times 10^{-8} \, m^2 \, s^{-1}$. The temperature gradient $100 \, K \, m^{-1}$ then creates in a ceramic body an adequate moisture gradient

of approx. 0.02 m^{-1}, i. e. one lower by an order of magnitude compared to the moisture gradient value. The effect of thermodiffusion can therefore be neglected for small temperature gradients when calculating water transfer in a water-saturated body when no moisture exchange occurs between the body and its environment.

CONCLUSION

1. The two thermal sources method described allows to study thermodiffusion of water in a saturated ceramic mix and to determine reliably the thermodiffusion coefficient.

2. The thermodiffusion coefficient in a water-saturated ceramic mix at $T = 319.6$ K amounts to $\bar{D}_T = 6 \pm 1 \times 10^{-10}$ m^2 s^{-1}.

3. The influence of thermodiffusion on water transfer in a saturated ceramic body with a saturated boundary can be neglected for small temperature gradients.

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VLIV TEPLOTNÍHO GRADIENTU NA PŘENOS VODY V NASYCENÉ KERAMICKÉ SMĚSI

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V práci je pro studium termodifúze vody v nasycené keramické směsi vypracována metoda dvou tepelných zdrojů a ukázán postup vyhodnocení termidifúzního koeficientu. Pro spolehlivé stanovení termodifúzního koeficientu touto metodou byly experimentálně určeny podmínky: a) reprodukovatelná příprava těles s homogenním a konstatním počátečním rozložením vlhkosti, b) konstantní a reprodukovatelný teplotní gradient, c) vyhovující kvalita izolační vrstvy, d) dosažení ustáleného stavu, e) rychlé zchlazení tělesa před jeho rozřezáním. Zjištěná hodnota termodifúzního koeficientu pro střední teplotu $T = 319,6$ K je $\bar{D}_T = (6 \pm 1) . 10^{-10}$ m^{2}s^{-1}. Z porovnání toků vody vyvolaných jednak koncentračním a jednak teplotním gradientem při stejné střední teplotě vyplynulo, že při výpočtu přenosu vody v nasyceném keramickém tělese, kdy nedochází k výměně vlhkosti mezi tělesem a jeho okolím, lze termodifúzi vody pro malé teplotní gradienty zanedbat.

Obr. 1. Teplotní a vlhkostní profil v tělese při $T = 319,6$ K.

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ВЛИЯНИЕ ТЕМПЕРАТУРНОГО ГРАДИЕНТА
НА ПЕРЕНОС ВОДЫ В НАСЫЩЕННОЙ КЕРАМИЧЕСКОЙ СМЕСИ

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Для исследования термодиффузии воды в насыщенной керамической смеси авторы разработали метод двух термических источников и приводят способ оценки термодиффузионного коэфициента. Для надежного определения термодиффузионного коэфициента с помощью упомянутого метода были экспериментальным путем установлены условия: а) воспроизводимое приготовление тел с однородным и постоянным распределением влаги, б) постоянный и воспроизводимый температурный градиент, в) соответствующее качество изоляционного слоя, г) получение установившегося состояния, д) резкое охлаждение тела до его разрезания.

Установленная величина термодиффузионного коэфициента для средней температуры $T = 319{,}6$ К составляет $D_T = (6 + 1) \cdot 10^{-10}$ м²с⁻¹. Из сопоставления потоков воды, вызываемых с одной стоорны концентрационным градиентом, а с другой стороны температурным градиентом при одинаковой средней температуре следует, что при расчете переноса воды в насыщенном керамическом теле, когда не проходит обмен влаги между телом и окружающей средой, можно диффузией воды вследствие небольших температурных градиентов пренебрегать.

Рис. 1. Профиль температуры и влаги в теле при $T = 319{,}6$ К.

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