Int. J. Heat Mass Transfer. Vol. 33, No. 6, pp. 1105–1120, 1990
Printed in Great Britain

0017-9310/90 $3.00+0.00

Description of transport of liquid in porous media—a study based on neutron radiography data

JOSEF PRAŽÁK and JAN TYWONIAK
Faculty of Civil Engineering, Czech Technical University, Prague, Thákurova 7, 166 29 Praha, Czechoslovakia

FRANTIŠEK PETERKA
Nuclear Research Institute, Řež near Prague, Czechoslovakia

and

TOMÁŠ ŠLONC
Institute for Research, Production and Application of Radioisotopes, Prague, Czechoslovakia

(*Received* 22 *September* 1988 *and in final form* 22 *February* 1989)

Abstract—The most frequently used approach to the description of liquid transfer in porous media is based on its analogy with the diffusion process. It introduces effective diffusivity $D(u)$ depending on actual moisture content u. On the basis of experimental data obtained by means of neutron radiography, it is shown that this function $D(u)$ cannot be regarded as a material characteristic because of its strong dependence on initial and/or boundary conditions. Alternative possibilities of the moisture transport description are discussed.

1. INTRODUCTION

THE PERMANENT interest in liquid transfer description, especially in connection with simultaneous heat transfer is explained by de Vries [1] by the following two facts:

—the importance of the subject for a (still expanding) multitude of applications;
—the lack of a comprehensive and satisfactory theory of the subject, despite much important work that has been carried out.

The contemporary status of the theory was characterized by de Vries with the words: "... usefulness of the theory ... was proven, but ... doubts remain about its predictive value. These doubts are a consequence of

—the limitations of the theory;
—uncertainty about the quality of the experimental procedures and data."

In some other works analysing systematically the subject [2, 3], the discrepancies between the theory and experiments are referred to.

The subject of this study is limited to a part of the complete problem: it analyses the diffusion type description of isothermal transport of liquid in porous media. New insight is hoped to be obtained by analysis based on high-quality experimental data provided by neutron radiography (NR). It represents a complete discussion of the results, part of which was presented in ref. [4].

The study has the following structure: the NR method, which is not too familiar in its application on the study of transport processes, is presented in Section 2. In Section 3, the problem considered is specified. The inversion problem for diffusion type equations is discussed in Section 4, its applications in Section 5. In Section 6, an alternative possibility for the description of isothermal liquid transport in porous media is introduced.

One comment to the references introduced in this work must be made: the literature concerned with the transport phenomena in porous media is extremely extensive. Let us mention in this connection the fact that systematic studies of the subject usually contain hundreds of references, e.g. 500 in ref. [3], 600 in ref. [5]. It is not possible, therefore, for us to introduce a complete bibliography in this study. That is why the references introduced here are only examples—we introduce them knowing that many other works could be introduced in their place.

2. NEUTRON RADIOGRAPHY

2.1. *General characteristic*

Neutron radiography (NR) is a visual non-destructive method of testing, having some features in com-

NOMENCLATURE

A, B, C coefficients for the general moisture distribution
$c_A, c_B, d_{AB}, u_{Bmax}$ parameters of the four-parametrical AB model
C' integration constant
d thickness of a sample
D diffusion coefficient
$\tilde{D}$ diffusivity expressed as a function of the x-coordinate
D_0 solution of the homogeneous inversion problem equation
D_t special solution of the inversion problem equation
D_c transport coefficient for concentration flux
D_u transport coefficient corresponding to the moisture potential description
F model function
g kernel of integral operator
I neutron flux
I_0 initial neutron flux
j moisture flux
j_A moisture flux caused by capillary mechanism
j_B moisture flux caused by diffusive mechanism
j_c concentration flux
j_i partial moisture flux
l_A length of the connected moisture area A
N number of target nuclei per unit volume
p pressure
R transmission of neutron flux
s_{AB} source term
t time
T actual value of time
u moisture content
u_A moisture content corresponding to capillary mechanism
u_B moisture content corresponding to diffusive mechanism
x spatial coordinate
X actual value of x-coordinate.

Greek symbols
μ chemical potential
ξ spatial variable
σ microscopic cross-section
Σ_{H_2O} macroscopic cross-section of water
Σ_M macroscopic cross-section of dry material
ψ moisture potential.

mon with more familiar X-ray testing. Since the first reactor neutron radiographs in 1956 [6], it has been used for many applications. Its area of application, basic principles and contemporary technical equipment as well as extended references are presented in refs. [7, 8].

In contrast to X-rays, neutrons can:

—be attenuated by light materials like water and hydrocarbons;
—penetrate through heavy materials like steel and lead;
—test highly radioactive objects.

On the other hand, the application of reactor neutron radiography is limited by the exclusivity of the necessary equipment. A typical field of its applications is, e.g. the quality assurance for nuclear reactor fuel.

In contrast to its technical difficulties, the theoretical basis of NR is simple: the intensity of a neutron flux is reduced as it passes through material according to the general law

$$\frac{dI}{dx} = I\sigma N \tag{1}$$

common to all radiation going through matter. For a sample of thickness d, it follows from equation (1) that

$$\frac{I(d)}{I_0} = e^{-\Sigma d}. \tag{2}$$

In this relation, the macroscopic cross-section Σ instead of the microscopic one σ is introduced by the relation

$$\Sigma = N\sigma. \tag{3}$$

For material with the moisture content u, the $\Sigma = \Sigma(u)$ dependence is well described by the linear function

$$\Sigma(u) = \Sigma_{H_2O}u + \Sigma_M. \tag{4}$$

It follows from relations (2)–(4), that we can determine the water content u from the value R (transmission). R is defined by the ratio of the two neutron fluxes—the incident flux upon the sample and the transmitted flux through the sample

$$R = \frac{I(u)}{I_0}. \tag{5}$$

The specificity of the neutron interaction is given by the fact that, in contrast to the α-, β- or γ-particles, the neutrons interact with the matter exclusively through nuclear forces and are therefore insensitive, e.g. to the distribution of electrons, which is connected with the chemical properties of matter.

For every experimental set-up, different technical problems must be solved. Without taking into account the problem of the neutron source (besides the reactor, the isotopic neutron source or accelerator with a suitable target can be used), they can be classified into the following groups.

(a) Collimation and purity of incident beam. For NR, the incident neutron beam must have certain geometrical properties—approximately parallel neutron trajectories and homogeneous flux through a cross-section of the beam in the place of the investigated sample. The content of the charged particles and/or γ in the beam must be maximally reduced.

(b) Detection of the transmitted neutrons. In contrast to the α-, β-, or γ-radiation, the neutrons cannot be registered directly—a two-step registration is necessary. In the first step, the reaction producing charged particles or γ takes place, the second step is the registration of them.

(c) Radioactive protection and manipulation with the sample.

2.2. *Application of NR for the study of water transport in porous media*

Every application of NR represents a specific solution of problems introduced in (a), (b) and (c) in Section 2.1. For the study of water transport in porous media, the NR method was adapted in the Nuclear Research Institute in Řež near Prague [9]. The materials used in the building industry were of special interest. The experimental set-up is shown in Figs. 1 and 2.

Let us introduce some data, which may be of interest.

One of the horizontal channels of the experimental reactor VVRS operating mostly at 5 MW was used as the neutron source. The basic characteristics of a neutron beam are the following: the neutron flux is 1.1×10^{11} n m^{-2} s^{-1}, the collimation ratio is 360. Neutron energies lie in the thermal range (0.03 eV).

The first step in neutron detection is the conversion of them into electrons in the reaction, schematically written as

$$^{157}\mathrm{Gd} + n \rightarrow {}^{158}\mathrm{Gd}^* \rightarrow {}^{158}\mathrm{Gd} + e_c.$$

As can be seen, this process itself is a two-step one, too. In the first step, the excited isotope of Gd is formed, in the second one, the deexcitation via electron conversion or γ-emission follows. (We limit ourselves to a simplified picture of the nuclear process.)

Different possibilities for the detection of electrons can be applied (see Fig. 2), but only the application of double emulsion film (Agfa) and its photodensitographical analysis (computer controlled microdensitometer Joyce–Loebl) can give the results of the desired quality.

The NR results are presented in Figs. 3 and 4. In Fig. 3, the wetting of a ceramic slab is shown by means of the neutron radiographs at three successive stages of the process—the dark colour corresponds to the saturated area of the sample. In Fig. 4, the computer-graphical picture of the wetting front (i.e. the area marked by arrows in Fig. 3(c)) is introduced for three different materials. In this figure, as well as at other places, the water content u is given in relative volume units (r.u.) giving the relative part of the whole volume occupied by water.

Three types of materials with different inhomo-

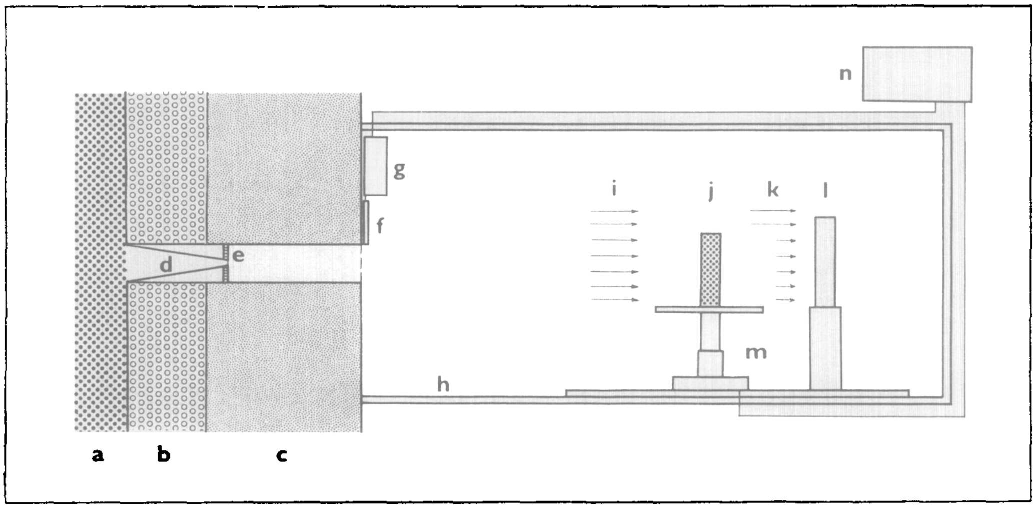


FIG. 1. Experimental set-up: a, core; b, water moderator; c, biological shield; d, convergent collimator; e, hole 8 mm, Bi filter; f+g, movable shutter; h, boron-plastic shield; i, initial neutron flux; j, sample; k, neutron flux; l, Gd foil with film; m, movable support; n, control unit.

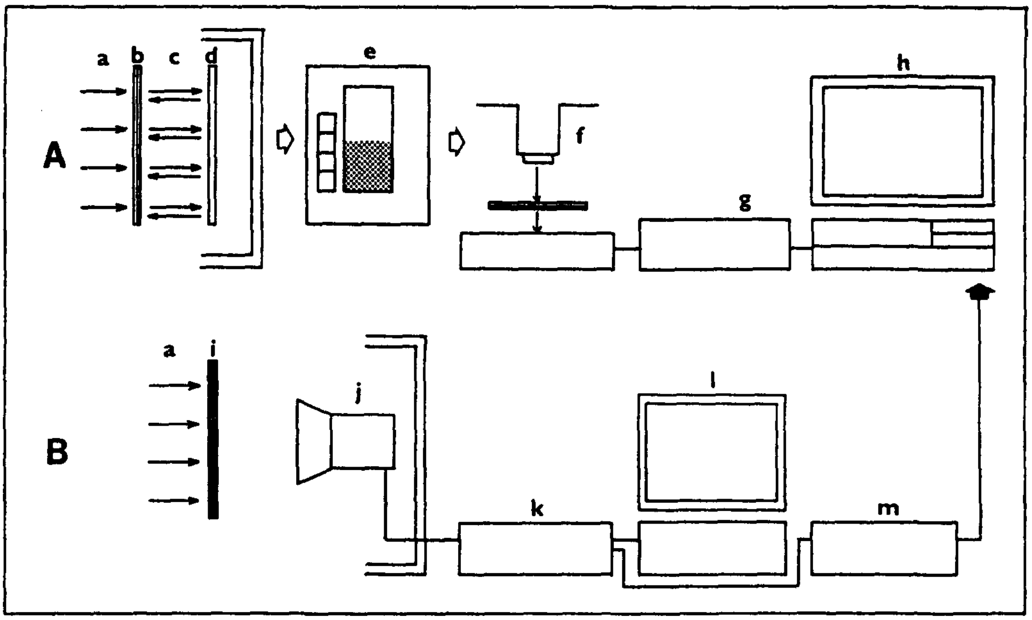


FIG. 2. Methods of visualization/digitalization of experimental results: A, photo-chemical treatment; B, application of TV system. a, neutron flux; b, film; c, conversion process; d, Gd foil; e, neutronogram; f, microdensitometer; g, generator, multimeter, counter; h, computer, graphical printer; i, fluorescent foil; j, high-sensitivity TV camera; k, camera controller; l, videorecorder; m, A/D convertor, image memory.

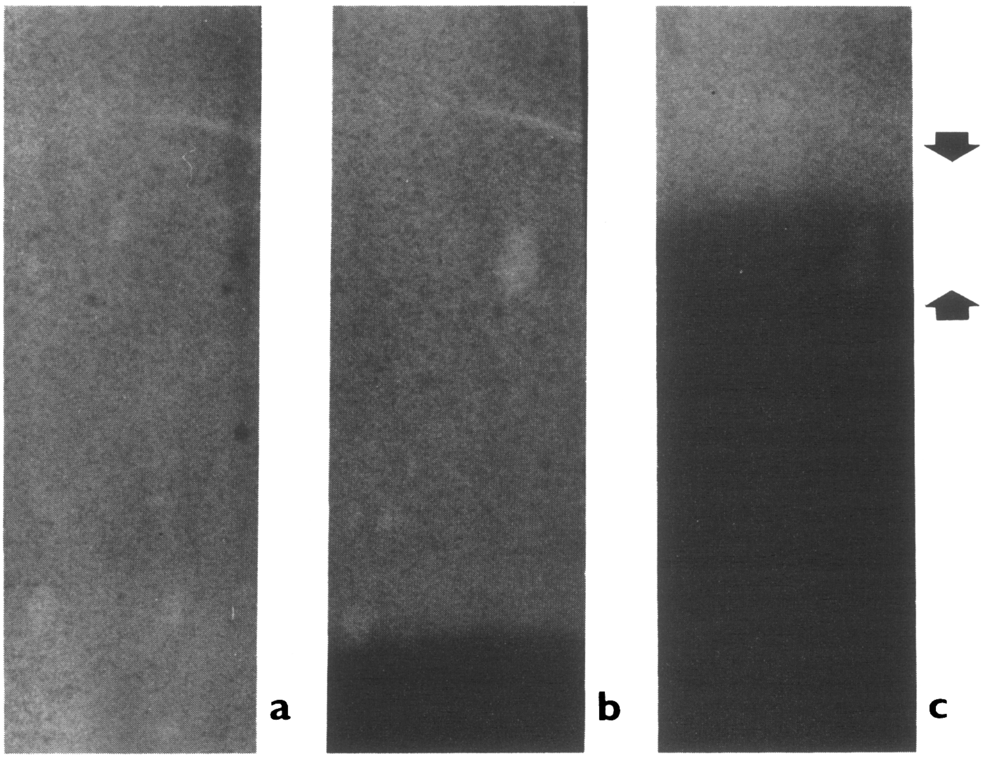
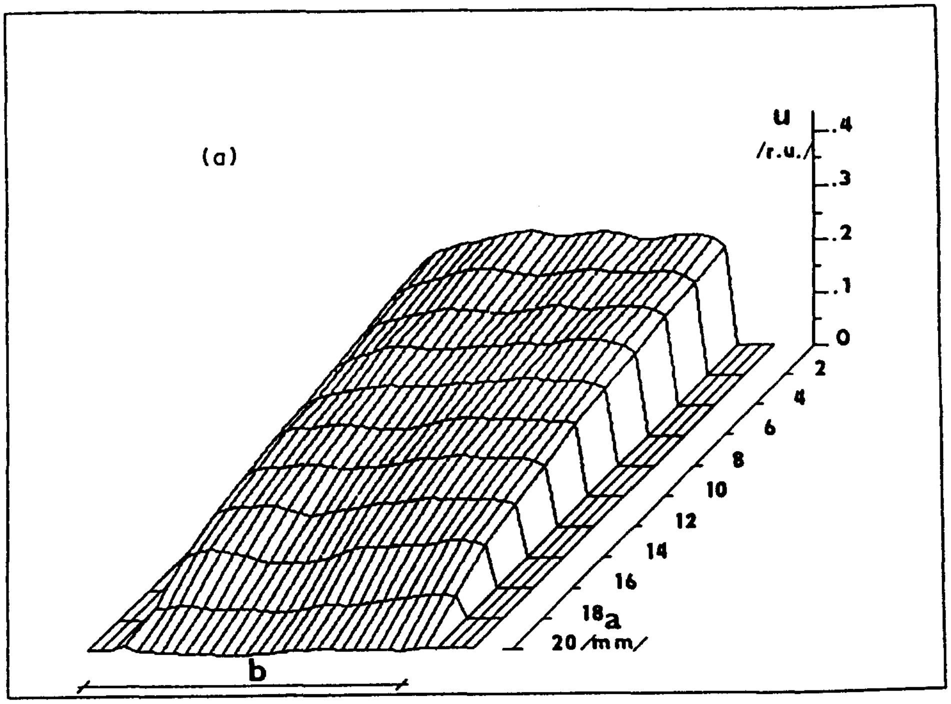


FIG. 3. Examples of neutronograms: (a)–(c) different stages of a wetting process.



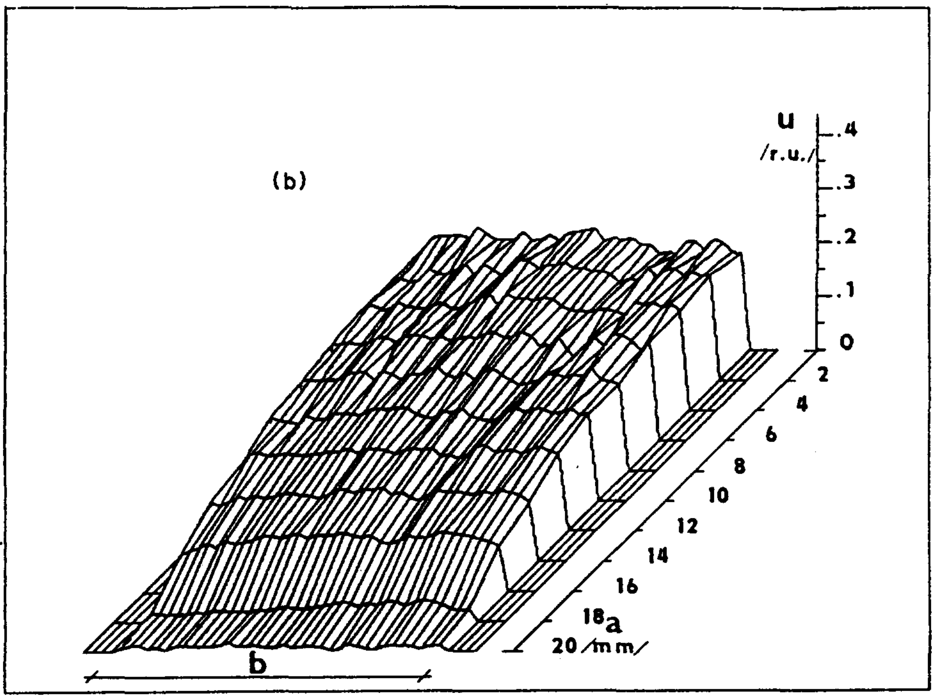


FIG. 4. Detail of the wetting front: (a) ceramic (b = 25 mm); (b) limesand brick (b = 36 mm); (c) areated concrete (b = 22 mm) (u relative moisture content (r.u.)).

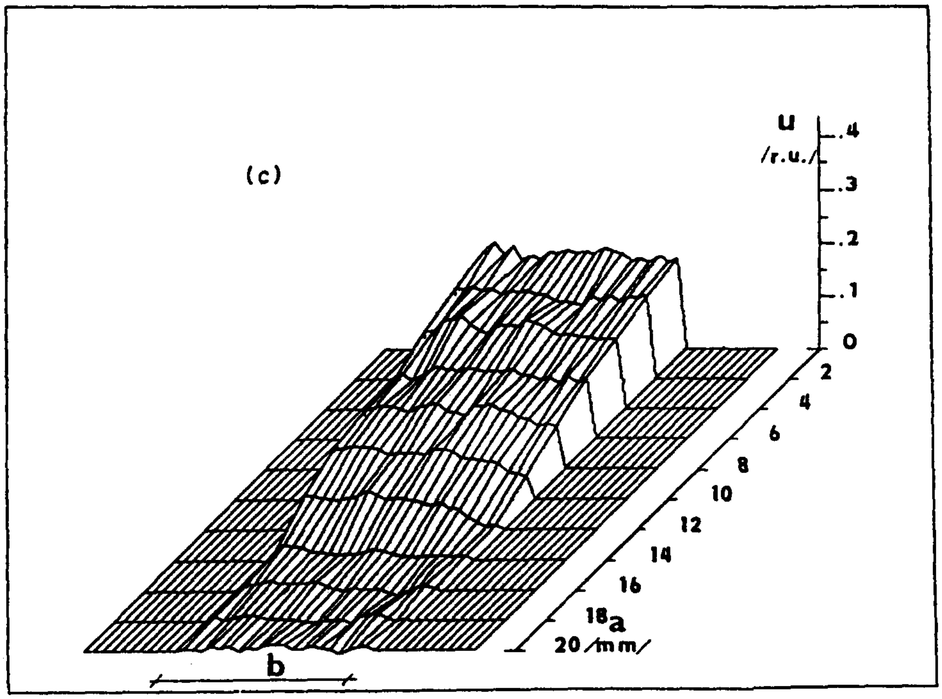


FIG. 4(c).

geneity ranges are presented:

(a) high-quality, vacuum pressed ceramic;
(b) limesand brick, laboratory quality;
(c) areated concrete, laboratory quality.

Typical dimensions of samples were 4 × 2 × 15 cm.

3. DEFINITION OF THE PROBLEM

The transport of liquid in porous materials is commonly described by the diffusion type equation [10–16]

$$\partial_t u = \operatorname{div}\,(D(u)\,\operatorname{grad} u). \qquad (6)$$

This equation describes the evolution of the moisture field $u(x, t)$ by means of the moisture-dependent function $D(u)$, which is supposed to be a material characteristic.

Equation (6) arises as a combination of the continuity equation

$$\partial_t u + \operatorname{div} \mathbf{j} = 0 \qquad (7)$$

and the empirical equation

$$\mathbf{j} = -D(u)\cdot \operatorname{grad} u. \qquad (8)$$

For a one-dimensional (or quasi one-dimensional) situation, equation (6) reduces to

$$\partial_t u = \partial_x (D(u)\partial_x u). \qquad (9)$$

Equation (7) is a universal physical law, but equation (8) is only a commonly used supposition. Let us discuss it.

The most general form of the dependence of the mass flux $\mathbf{j}(\mathbf{x}, t)$ on $u(x, t)$ can be expressed as

$$\mathbf{j}(\mathbf{x}, t) = \int \mathbf{g}(\mathbf{x}', \mathbf{x}, t', t) u(\mathbf{x}', t')\, \mathrm{d}\mathbf{x}'\, \mathrm{d}t'. \qquad (10)$$

The integration range for $\mathbf{x}'$ is the whole space E3, $t' \in (-\infty, t)$. Equation (10) expresses the fact that the flux at x and time t depends on the distribution of liquid in the whole space at all the preceding times. The properties of the actual medium are contained in the kernel $\mathbf{g}(\mathbf{x}', \mathbf{x}, t', t)$ of the integral operator.

The necessity of the invariance of the description under the spacial and temporal translations leads to a reduction of the kernel

$$g(\mathbf{x}', \mathbf{x}, t', t) = g(\mathbf{x}-\mathbf{x}', t-t'). \qquad (11)$$

It represents the reduction of a number of variables in g from 8 to 4. The other reduction—to the class of 'no memory' materials—leads to

$$\mathbf{j}(\mathbf{x}, t) = \int \mathbf{g}(\mathbf{x}-\mathbf{x}') u(\mathbf{x}', t')\, \mathrm{d}\mathbf{x}'. \qquad (12)$$

If some mathematical suppositions are fulfilled, the Taylor expansion of $u(\mathbf{x}',t')$ around the point $(\mathbf{x}, t)$ can be made and $\mathbf{j}(\mathbf{x}, t)$ can be written as an infinite sum of derivatives of $u(\mathbf{x}',t)$. Symbolically

$$j(x, t) = Au(x, t) + B(\operatorname{grad} u(x, t)) + C(\operatorname{grad}\,(\operatorname{grad} u(x, t))) + \cdots. \qquad (13)$$

The coefficients $A, B, \ldots$ (which are constants of a different tensor range) are the result of the integration in equation (12), e.g.

$$B = \int g(\xi)\xi \, d\xi. \tag{14}$$

The properties of the medium are therefore now contained in those coefficients.

For a macroscopically homogeneous medium, the $A = 0$ means that no fluxes are present for the homogeneous distribution of liquid. The most simple applicable approximation of the general relation (10) is, therefore, for a homogeneous (quasi) one-dimensional liquid transport relation

$$j(x, t) = B\,\partial_x u(x, t) \tag{15}$$

where B is a characteristic constant of the material. The demonstrated way from equation (10) to equation (15) represents a systematic reduction of the complex (but practically not applicable) description to its most simple approximation. At this stage, approximation (15) must be regarded as a hypothesis and it must be verified in the experiments. But already the simplest one shows that relation (15) is oversimplified. Therefore, a systematic approach needs the reduction of a number of simplifying assumptions. It means the consideration of higher members, e.g. of expression (13). But the description using higher derivatives of experimental values is principally an uncertain one.

It follows that for the progress in the description, a nonsystematical, *ad hoc* hypothesis concerning $j(x, t)$ is necessary. Equation (8) seems to be a very natural one, because it conserves formally the simple form of relation (15). Two other arguments can be used for hypothesis (8), too.

(1) For the saturated flows in porous media under the influence of pressure gradient, classical Darcy's law holds [17]

$$\mathbf{j} = -D \operatorname{grad} p \tag{16}$$

where D is a constant for a given medium. For not too high flow rates, this relation has been amply verified both experimentally and theoretically. Relation (8) seems to be a natural generalization of Darcy's law for unsaturated flows.

(2) The linearized theory of the irreversible thermodynamics (Onsager) gives for the concentration flux $\mathbf{j}_c(x)$ of one component in a solution the relation

$$\mathbf{j}_c(x) = -D_c \operatorname{grad} \mu(x). \tag{17}$$

For liquid transport in a porous medium, the existence of the moisture potential ψ, the quantity analogous to the chemical potential μ, is supposed. The ψ-potential depends on the local moisture content $u(x, t)$

$$\psi = \psi(u(x, t)). \tag{18}$$

The equation for the liquid flux analogous to equation (17) can therefore be expressed in the form

$$\mathbf{j} = D_u \frac{d\psi}{du} \operatorname{grad} u. \tag{19}$$

Introducing the definition

$$D(u) = D_u \frac{d\psi}{du} \tag{20}$$

we get relation (8) from relation (19).

The analogous 'thermodynamical' argumentation applied on the simultaneous mass and heat transfer leads to the widely used Luikov system [10, 18] of transport equations. In this approach, the mentioned hypothesis is transformed to the hypothesis concerning the existence of the potential ψ.

Summarizing, we can say that equation (6) contains a hypothesis which can be expressed in the explicit way as follows. Every porous medium is characterized by a specific material function $D = D(u)$, which controls the evolution of the moisture field $u(x, t)$ according in the medium to the diffusion type equation (6).

As was mentioned in the Introduction, this hypothesis has already been tested many times, but the conclusions are not unique (only one exception is found in ref. [19]). This uncertainty of the results can be explained by the fact that no really satisfactory non-destructive method for the determination of the moisture content u was used. Therefore, the application of NR can bring a new quality into the testing of the mentioned hypothesis. This point will be explained in the next section.

4. THE INVERSION PROBLEM FOR THE DIFFUSION-TYPE EQUATION

Supposing equation (6) to be the equation governing the motion of liquid in a porous medium and $D(u)$ the material characteristic of this medium. For applications, we need an algorithm for determining $D(u)$ from experimental data. We shall discuss this question for one special experimental situation.

Let us have the moisture distribution $u(x, T)$ describing the situation in a one-dimensional semi-infinite sample at time T (Fig. 5(a)). The conditions of the process are

$$u(x, 0) = 0 \quad \text{for } x \in (0, \infty)$$
$$u(0, t) = u_{\max} \quad \text{for } t \in (0, \infty). \tag{21}$$

The point X limits the interval of non-zero values of the function $u(x, T)$. It must be $X < \infty$ because of the finite speed of the displacement of the moisture. If the function $u(x, T)$ represents one-to-one correspondence of the interval $(0, X)$ on the interval $(0, u_{\max})$, then the function $D(u(x, t))$ can be expressed as a function $\bar{D}(x)$ of the variable x, for a fixed T

$$\bar{D}(x) = D(u(x, T)). \tag{22}$$

Equation (6) can then be expressed in the form

$$\frac{d}{dx}\bar{D}(x)[\partial_x u]_T + \bar{D}(x)[\partial_{xx} u]_T = [\partial_t u]_T. \tag{23}$$

The functions in square brackets are the functions of

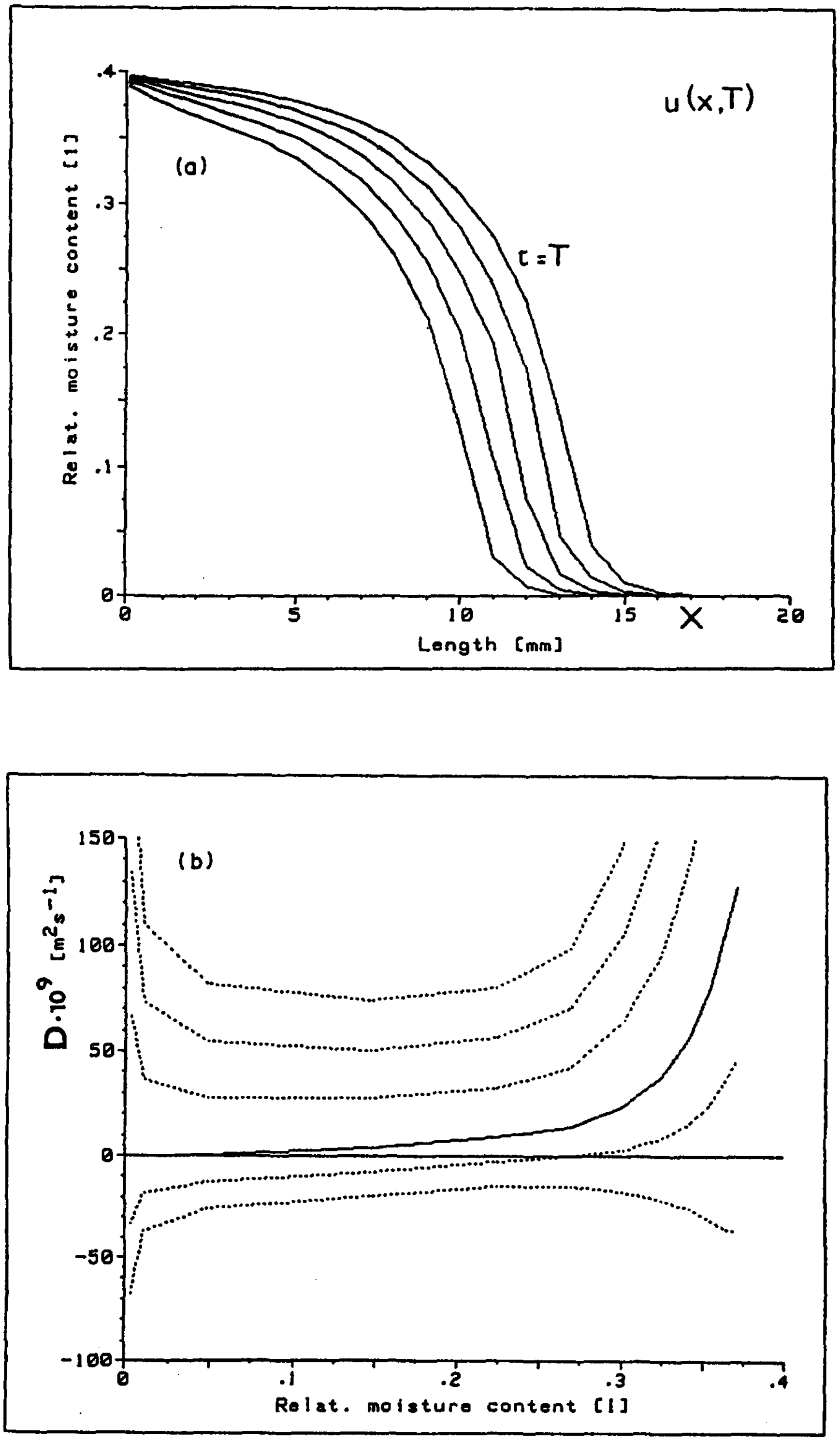


FIG. 5. Moisture distribution in one-dimensional semiinfinite sample (a), corresponding solution of inversion problem (b) (u relative moisture content (r.u.), x length (mm), t time (s), $u(x, T)$ actual moisture distribution in time T, $u(x, T) > 0$ for $x \in (0, X)$).

x. They can be gained from the experiment, in principle. Equation (23) is an ordinary differential equation for $\bar{D}(x)$. We can get the general solution of it in the standard way: the solution $D_0(x)$ of the corresponding homogeneous equation is

$$D_0 = \frac{C'}{[\partial_x u]_T}. \quad (24)$$

One special solution of equation (23) is, e.g.

$$D_1 = \frac{\int [\partial_t u]_T \, dx}{[\partial_x u]_T}. \quad (25)$$

The general solution of equation (23) is

$$D = \frac{C' + \int [\partial_t u]_T \, dx}{[\partial_x u]_T}. \quad (26)$$

Equation (26) represents a one-dimensional continuum of solutions of equation (23) in the mathematical sense. A physical condition must be applied to choose the solution of the physical problem from them. The condition $X < \infty$ makes only the $D(u)$ with

$$\lim_{u \to 0^+} D(u) = 0 \quad (27)$$

admissible.

In Fig. 5(a), the situation for

$$\lim_{x \to X} \partial_x u(x, T) = 0 \quad (28)$$

is represented. This case is interesting due to the fact that all the solutions apart from the physical one diverge for $u \to 0$. This fact can lead to an important numerical instability in computer programs searching for $D(u)$ near $u = 0$.

Equation (26) together with condition (27) is the exact solution of the inverse problem for equation (6), but it may not be of practical importance, when no experimental method can give the functions $[\partial_x u]_T$ and $[\partial_t u]_T$. Especially, the function $[\partial_t u]_T$ is very difficult to measure (approximate), because of the necessity of the application of a non-destructive method for it. Usual non-destructive methods for measuring the moisture content [20, 21] have two main disadvantages:

—accuracy not exceeding 5%;
—too big spatial range of averaging necessary.

It seems that only NR with the sensitivity of 10^{-3} g H_2O cm^{-3} and high resolution of the image (0.3 mm) is the method, in connection with relations (26) and (27), which can be used for determination of $D(u)$.

Together with the destructive methods of moisture measurement [22], the different integral methods for the inverse problem are used. Usually, those methods are based on Matano's idea [23] (associated sometimes with the names of Bruce and Klute [24]). The integral form for $D(u)$ does not contain the constant C' explicitly, that is why the numerical instability mentioned above can be disregarded and the unphysical solution (see Fig. 5) interpreted as a physical one [25].

The most important inconvenience of the destructive methods of moisture measurement is the fact that they limit essentially the number of situations which can be investigated. The impossibility of making more than one measurement during the process, leads to the necessity to start the wetting only with conditions (21). That is why the destructive methods do not give the possibility to measure the $D(u)$ for different initial and/or boundary conditions and to test the dependence of $D(u)$ on these conditions. Of course, the $D(u)$ being a characteristic material function must be independent of initial and/or boundary conditions.

On the other hand, relation (26) can be used rather generally, as can be seen. The only limitation is the monotony of the distributions $u(x, t)$. This fact makes it possible for us to determine the function $D(u)$ for different processes and to test in this way the hypothesis supposing $D(u)$ to be a material characteristic.

5. EXPERIMENTAL RESULTS

Experiments with different porous materials were performed. From the point of view of homogeneity of the used structures, the materials introduced in Sections 2.2(a)—ceramics—and (c)—areated concrete—can be regarded as limits. We do not introduce the results for materials having the range of inhomogeneity of that of areated concrete. There are two reasons for it.

—The inhomogeneities of measured distributions $u(x, t)$ need special mathematical management (averaging) making it impossible to distinguish, what is really an experimental result and what arises from the averaging.

—The range of pore diameters makes it necessary to take gravitational forces into account by describing the transport phenomena; equation (6) alone is evidently insufficient.

Different types of experiments were performed. We shall discuss three of them.

—Type I. Type I is the simple wetting of an initially dry material from one non-insulated side which is in contact with water—the typical $u(x, t)$-curves are presented in Fig. 6(a). The corresponding $D(u)$ obtained by the application of equation (26) is shown on Fig. 6(b).

—Type II. After some time developing the moisture distribution like in type I, the sample is insulated completely. The redistribution of the liquid in the insulated sample is investigated. The typical $u(x, t)$- and $D(u)$-curves are presented in Figs. 7(a) and (b), respectively.

To compare the results obtained from types I and II experiments, respectively, we introduce both $D(u)$-curves once more in one picture (Fig. 8).

—Type III. Type III experiment is drying of initially

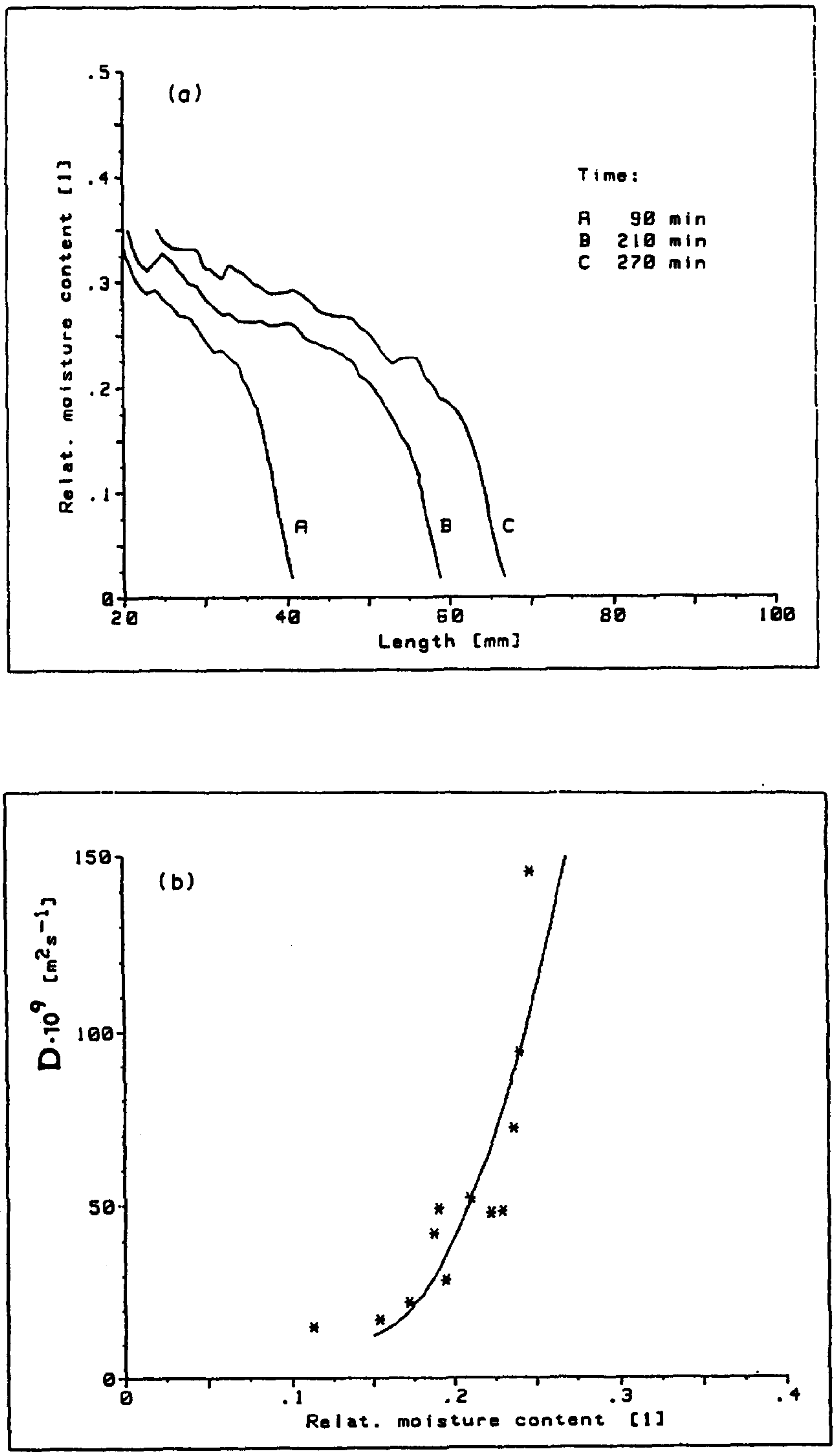


FIG. 6. Evolution of moisture distribution—wetting of initially dry sample—exp. I (a) and corresponding effective diffusivity (b).

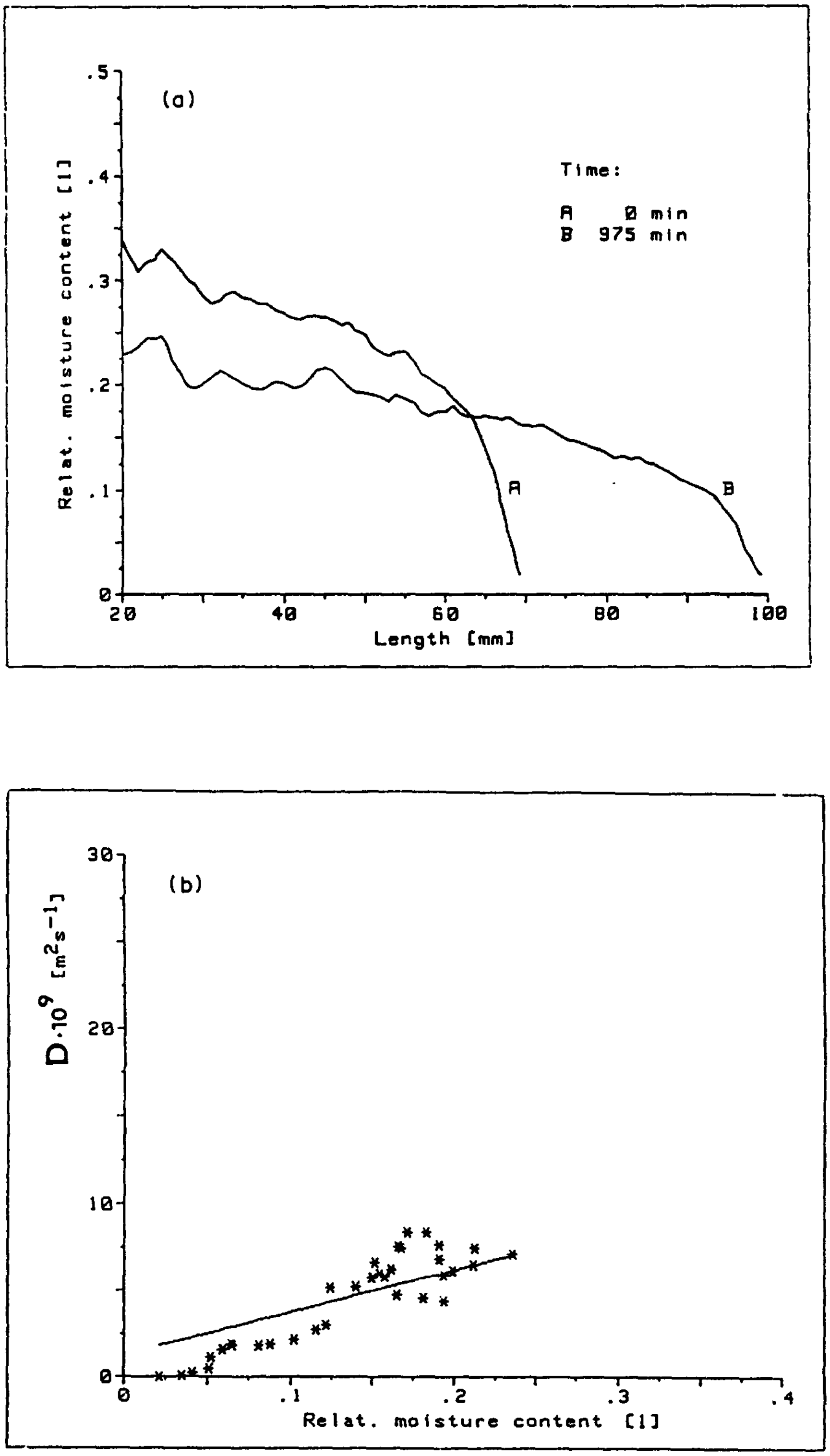


FIG. 7. Evolution of moisture distribution—redistribution in insulated sample—exp. II (a) and corresponding effective diffusivity (b).

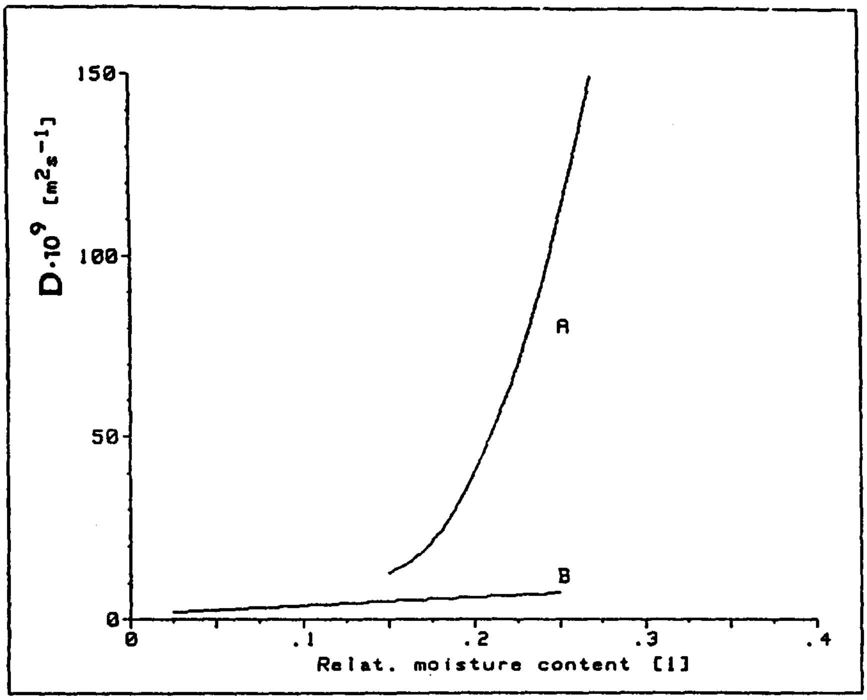


FIG. 8. Comparison of the effective diffusivity from exp. I (A) and that from exp. II (B).

completely saturated material. A typical result is presented in Figs. 9(a) and (b). We see that $D(u)$ for drying differs dramatically for different times of the same process.

6. DISCUSSION

Summarizing the results of the preceding section, we see that it is not possible to consider the effective diffusivity $D(u)$ to be a characteristic constant of the material—it depends strongly on conditions in which the process develops.

For the description of liquid transport in porous media, two possible ways can be followed:

—the application of equation (6), but with different functions $D(u)$ for different boundary conditions;

—construction of an alternative model; this model should have the characteristics (preferably constants) independent of external conditions and of the type of process.

The latter possibility will be discussed shortly. The physical cause of the fact that the different effective diffusivities correspond to different boundary conditions can be explained by the different transport mechanisms composing the summary transport phenomenon. They react in a different way on the changing of boundary conditions. By constructing a conceptual model, it is therefore necessary to describe the resulting flux $j(x)$ as a sum of partial fluxes $j_i(x)$ corresponding to the specific mechanisms and having a specific reaction on different boundary conditions.

This way the description can be expressed in the form of system integro-differential equations with the desired generality. We shall limit ourselves to one special example of this approach.

In this model, two transport mechanisms are considered—the capillary transport (mechanism A) and the diffusive transport (mechanism B). The main feature of the model is to separate not only fluxes A and B, but also the corresponding liquid contents u_A and u_B. This fact must be compensated by introducing a source term into the equations. This term makes the interaction of the two transport mechanisms possible. In the (quasi) one-dimensional situation, the flux A is determined by the fact that inflow A into the sample is given by

$$j_A(0, t) = c_A(l_A(t))^{-1} \tag{29}$$

where $l_A(t)$ is the range of the connected moistured area A in contact with the boundary. Flux B is determined by the equation

$$j_B(x, t) = -c_B\, \partial_x u_B(x, t). \tag{30}$$

The continuity equations hold separately for A and B

$$\partial_t u_A(x, t) = -\partial_x j_A(x, t) - s_{AB}(x, t) \tag{31}$$

$$\partial_t u_B(x, t) = -\partial_x j_B(x, t) + s_{AB}(x, t). \tag{32}$$

The source term s_{AB} is supposed to have the simple form

$$s_{AB}(x, t) = F(u_B(x, t)) \tag{33}$$

for non-zero values of $u_A(x, t)$.

Numerical experiments show that already this simple two-mechanism (AB) model with suitable

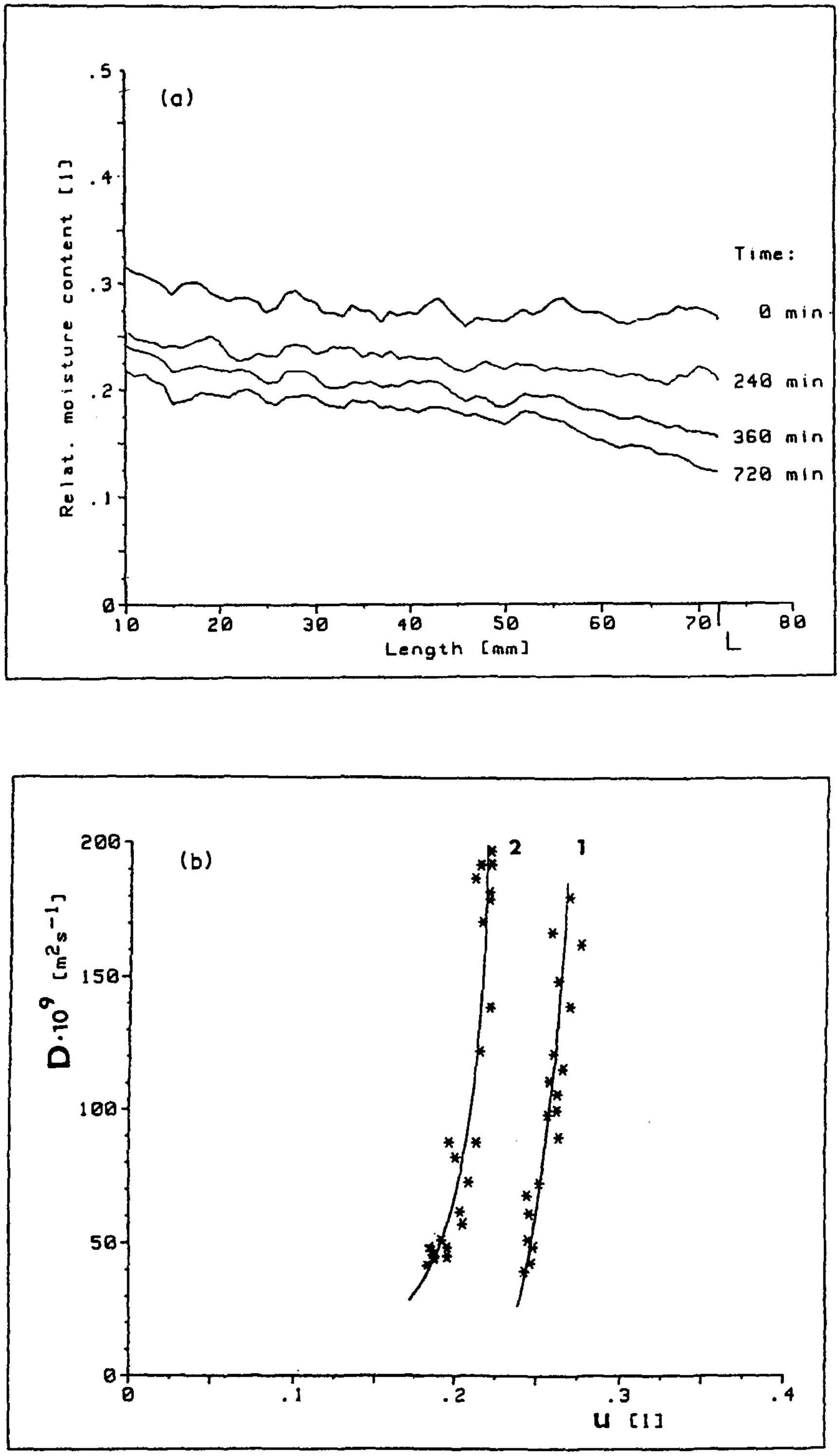


FIG. 9. Evolution of moisture distribution—drying of initially wet sample—exp. III (a) and corresponding effective diffusivities (b); (1) corresponds to the time interval of 0–240 min, (2) to that of 360–720 min (L, free surface of a sample).

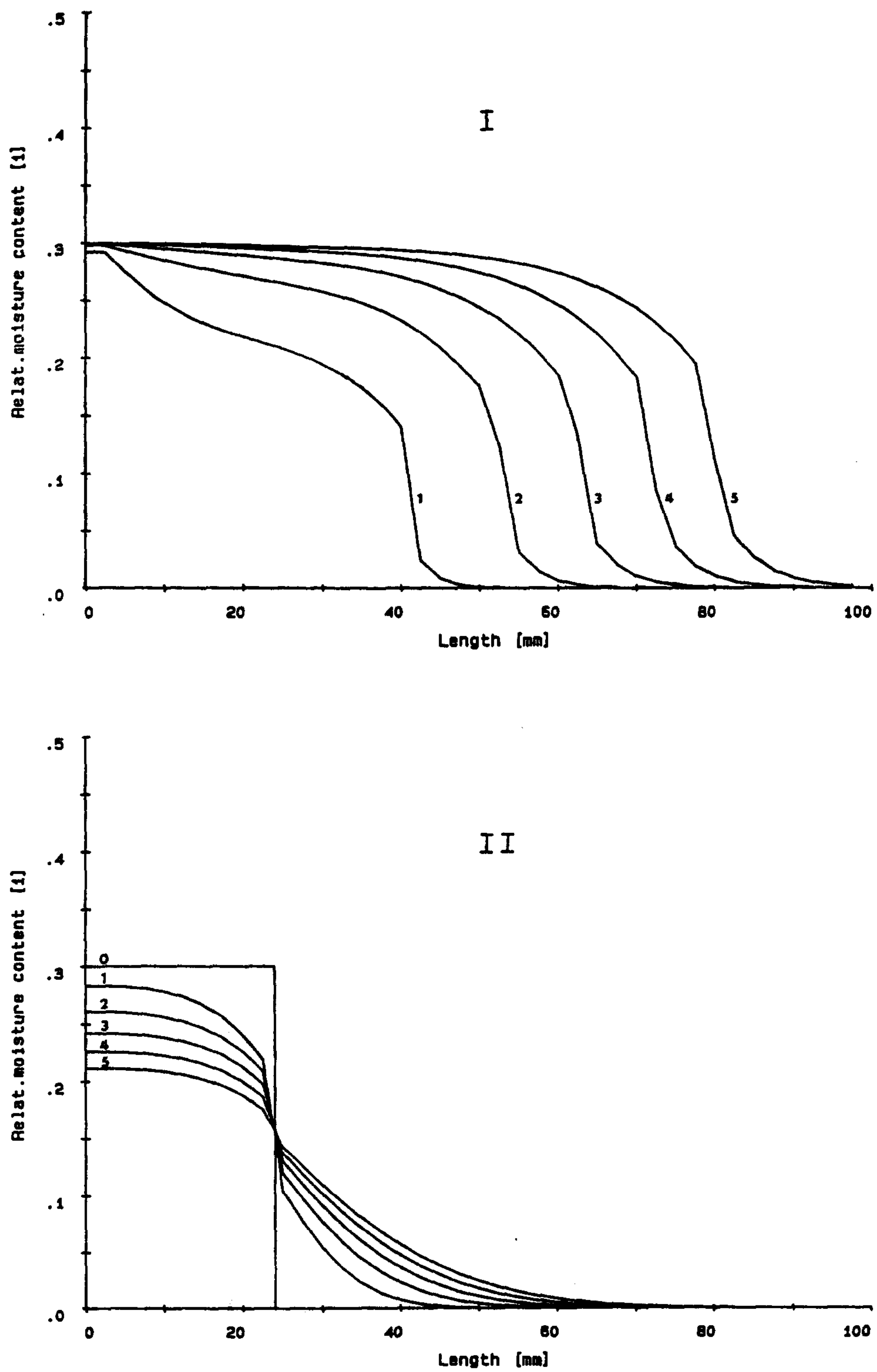


FIG. 10. Simulation of experiments I–III, respectively, by means of the four-parametrical AB model. The numbers denote the succession of moisture distributions in equidistant time intervals—actual time scale can be chosen arbitrarily.

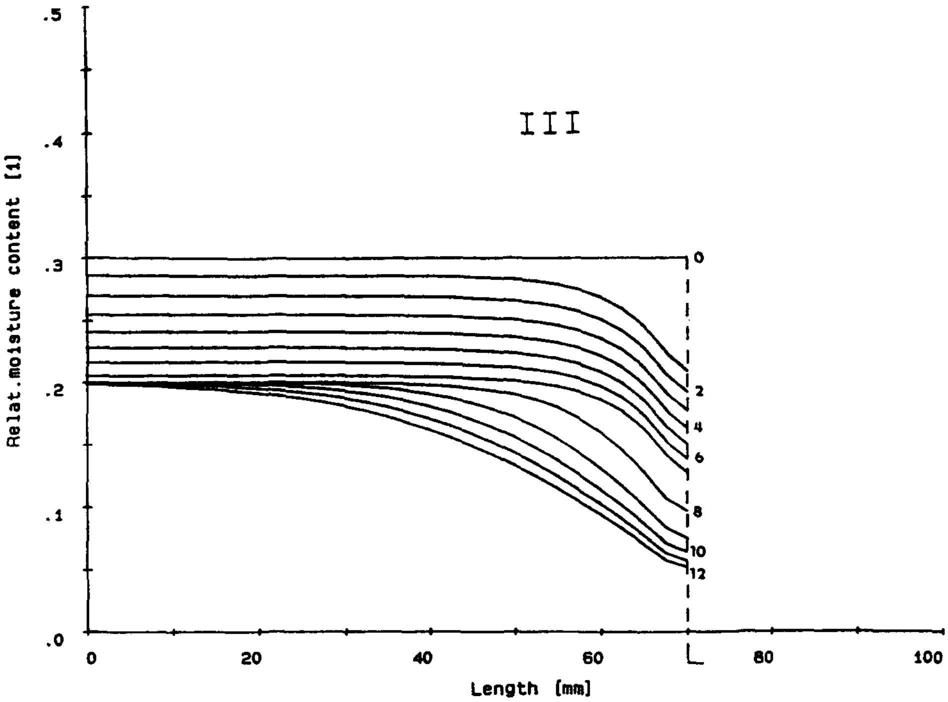


FIG. 10(III).

function F, can qualitatively well reproduce the results of all three types of experiments (I, II, III) mentioned in Section 5 by means of a set of 4–6 constants, which can be regarded as material characteristics. An example is presented in Fig. 10. For the introduced simulations, the term s_{AB} (33) has the form

$$s_{AB}(x,t) = d_{AB} \cdot (u_{B\max} - u_B(x,t)) \tag{34}$$

and every connected moisture area A loses its moisture simultaneously. In this example, four independent constants are used. Model AB (and the analogical ones) is developed with the intention to characterize actual porous material by a simple set of constants, which determine fully the comportment of it—at least for some classes of applications.

Acknowledgements—The authors wish to thank Z. Hrdlička (Nuclear Research Institute, Řež) for his collaboration in the early stage of the work and F. Oujiří (Department of Silicate, University of Chemical Technologies, Prague) for the preparation of special samples.

REFERENCES

1. D. A. de Vries, The theory of heat and moisture transfer in porous media revisited, *Int. J. Heat Mass Transfer* **30**, 1343 (1987).
2. A.-C. Andersson, Verification of calculation methods for moisture transport in porous building materials, Swedish Council for Building Research D6 (1985).
3. J. van Brakel, Capillary liquid transport in porous media, Thesis, Delft, The Netherlands (1975).
4. J. Pražák, J. Tywoniak, F. Peterka and T. Šlonc, Bemerkungen zur Beschreibung des Flussigkeitstransports in porosen Baumaterialien, *Gesundheits-Ingenieur-Haustechnik-Bauphysik-Umwelttechnik* **110**, 308 (1989).
5. K. Kiessl und K. Gertis, Feuchtetransport in Baustoffen. Eine Literaturauswertung zur Erfassung hygrischer Transportphänomene, Forschungsberichte aus dem Fachbereich Bauwesen der Universitat—Gesamthochschule Essen, 13 (1980).
6. J. Thewlis and R. T. P. Derbyshire, A.E.R.E. M/TN 37 (1956)—see ref. [8].
7. J. P. Barton and P. von der Hardt (Editors), *Neutron Radiography, Proc. First World Conf.*, San Diego, California, 7–10 December (1981).
8. P. von der Hardt and H. Rottger (Editors), *Neutron Radiography Handbook*. D. Reidel, Dordrecht (1981).
9. F. Peterka and T. Šlonc, Aplikace neutronové transmisní analýzy pro zjištění distribuce volné vody ve vzorku keramického materiálu, Report, Institute for Nuclear Research, Řež near Prague (1988).
10. A. V. Luikov, Systems of differential equations of heat and mass transfer in capillary-porous bodies (review), *Int. J. Heat Mass Transfer* **18**, 1 (1975).
11. E. R. Eckert and R. M. Drake, Jr., *Analysis of Heat and Mass Transfer*. McGraw-Hill, New York (1972).
12. O. Krischer and W. Kast, *Die wissenschaftlichen Grundlagen der Trocknungstechnik*, Dritte Auflage. Springer, Berlin (1978).
13. J. R. Philip, Theory of infiltration, *Adv. Hydrosci.* **5**, 215 (1969).
14. P. Crausse, G. Bacon and S. Bories, Etude fondamentale des transferts couples chaleur-masse en milieu poreaux, *Int. J. Heat Mass Transfer* **24**, 991 (1981).
15. C. Hall, Water movement in porous building materials—I. Unsaturated flow theory and its application, *Bldg Environ.* **12**, 117 (1976).
16. H. Darcy, *Les fontaines publiques de la ville de Dijon*. V. Dalmont, Paris (1856).
17. Bu-Xuan Wang and Zhao-Hong Fang, Water absorption and measurement of the mass diffusivity in porous media, *Int. J. Heat Mass Transfer* **31**, 251 (1988).

18. A. V. Luikov, *Heat and Mass Transfer in Capillary-porous Bodies*. Pergamon Press, Oxford (1966).
19. M. Hallaire and S. Henin, Sur la non validité de l'equation de conductivité pour exprimer le mouvement d'eau non saturante dans un sol, *C. R. Acad. Sci.* **246**, 1720 (1958).
20. A. Pande, *Handbook of Moisture Determination and Control. Principles, Techniques, Applications*. Marcel Dekker, New York (1975).
21. A. Wexler (Editor), *Humidity and Moisture. Int. Symp. on Humidity and Moisture*, Washington, 1963. Reinhold, New York (1965).
22. J. Mitchell, Jr. and D. M. Smith, *Aquametry—A Treatise on Methods for the Determination of Water* (in Russian). Chimija, Moskva (1980).
23. C. Matano, On the relation between the diffusion coefficient and concentration of solid metals, *Japan J. Phys.* **8**, 109 (1933)—see J. P. Stark, *Solid State Diffusion* (in Russian). Energija, Moskva (1980).
24. R. R. Bruce and A. Klute, The measurement of soil moisture diffusivity, *Soil. Sci. Soc. Am. Proc.* **20**, 458 (1956).
25. J.-C. Bacri, C. Leygnac and D. Salin, Evidence of capillary hyperdiffusion in two-phase fluid flows, *J. Phys. Lett.* **46**, 467 (1985).

DESCRIPTION DU TRANSPORT DE LIQUIDE DANS UN MILIEU POREUX—UNE ETUDE BASEE SUR DES DONNEES DE RADIOGRAPHIE NEUTRONIQUE

Résumé—L'approche la plus utilisée dans la description du transfert de liquide dans les milieux poreux est basée sur son analogie avec le mécanisme de diffusion. Elle introduit une diffusivité effective $D(u)$ qui dépend du contenu en humidité u. A partir de données expérimentales obtenues par radiographie neutronique, on montre que cette fonction $D(u)$ ne peut être regardée comme une caractéristique matérielle à cause de sa forte dépendance vis-à-vis des conditions initiales et aux limites. On discute différentes possibilités de description du transport d'humidité.

BESCHREIBUNG DES FLÜSSIGKEITSTRANSPORTS IN EINEM PORÖSEN MEDIUM AUFGRUND EINER UNTERSUCHUNG MITTELS NEUTRONEN-RADIOGRAFIE

Zusammenfassung—Die gebräuchlichste Betrachtungsweise bei der Beschreibung des Flüssigkeitstransports in porösen Medien beruht auf der Analogie mit dem Diffusionsprozeß. Dabei wird die effektive Diffusivität $D(u)$ in Abhängigkeit vom aktuellen Feuchtigkeitsgehalt u eingeführt. Auf der Grundlage von Versuchsergebnissen, die mit Hilfe der Neutronen-Radiografie gewonnen worden sind, zeigt sich, daß diese Funktion $D(u)$ nicht als Materialeigenschaft betrachtet werden darf. Dafür ist sie zu stark von Anfangs- und/oder Randbedingungen abhängig. Abschließend werden alternative Möglichkeiten zur Beschreibung des Feuchtetransports diskutiert.

ОПИСАНИЕ ПЕРЕНОСА ЖИДКОСТИ В ПОРИСТЫХ СРЕДАХ—ИССЛЕДОВАНИЕ НА ОСНОВЕ ДАННЫХ НЕЙТРОННОЙ РАДИОГРАФИИ

Аннотация—Наиболее часто применяемый подход к описанию переноса жидкости в пористых средах базируется на его аналогии с диффузионными процессами. При этом вводится эффективный коэффициент диффузии $D(u)$, зависящий от истинного влагосодержания u. На основе экспериментальных данных, полученных методом нейтронной радиографии, показано, что данная функция $D(u)$ не может считаться материальной характеристикой в силу ее сильной зависимости от начальных и/или граничных условий. Обсуждаются альтернативные возможности описания влагопереноса.