

A TRACER METHOD OF DETERMINING PORE-SPACE DEAD ZONES FOR COLLECTOR ROCKS

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A laboratory method is described for determining the parameters of pore-space dead zones in collectors.

Methods are being developed and tested for increasing oil extraction by pumping polymer solutions into the strata, with the displacement of oil under conditions close to mixing ones, e.g., by the use of CO₂, solvents, and micellar solutions.

As reagents are costly, they are usually employed at the margins, and the size of these constitutes an important technological parameter. If the size is larger than optimal, the consumption of reagent may not be compensated by the additional extracted oil. The optimum size is dependent not only on the geometry of the space between boreholes, by gravitational effects, by mobility, and so on, but also is determined by the microscopic inhomogeneity in the pore space, in particular the presence of dead-end pores or zones with relatively little mass transfer, which may be called stagnant zones. The proportion of such zones is indicated by miscible displacement [1] as varying from 0 to 60% in accordance with the structure of the pore space and the displacement conditions. Therefore, research on these zones is important in practical and theoretical respects [2-5]. Unfortunately, there are only a few papers [1-6] that deal with experiments on this.

Here we describe a method of determining the zone parameters from the passage of a gas tracer. The porous medium is represented as a sequence of ideal-mixing cells with stagnant zones [5], and it is possible to determine the size of these zones by the tracer method. The proportion of such zones is determined by the broadening of the trace volume when a neutral minor component is added to the liquid passing through the specimen. The descending branch of the output curve has a pronounced tail, and a bell-shaped function may be used for the curve as a first approximation [6]. An additional parameter is also used to determine the size of the stagnant zones, namely the tortuosity of the channels, which is derived from statistical processing on sections.

The tracer-broadening curve may be analyzed to determine in addition the rate of exchange p of material between the stagnant zones and the flow channels, together with the transfer coefficient p/q and the length l of an ideal-mixing cell, which eliminates the determination of the tortuosity. The following equations describe the variation in the tracer concentration at the exit from the porous medium (Fig. 1):

$$t < c \quad h(t) = a \exp[-b(t-c)^2], \quad (1)$$

$$t > c \quad h(t) = a \exp[-b(t-c)^2] + d \exp(-\gamma t), \quad (2)$$

$$a = \left(1 - \frac{L}{l} \frac{p}{q}\right) \frac{u}{q(1-\alpha)\sqrt{2\pi lL}}, \quad b = \frac{u^2}{2(1-\alpha)^2 lL}, \quad (3)$$

$$c = \frac{(1-\alpha)L}{u}, \quad d = \left(\frac{p}{q}\right)^2 \frac{uL}{q\alpha l^2}, \quad \gamma = \frac{p}{q} \frac{u}{\alpha l}.$$

There are connecting tubes to the specimen and from the specimen to the detector, so it is necessary to identify the contribution from the specimen to the total tracer-broadening curve. For this purpose one records the curve $Z(t)$ for the system with the specimen, and

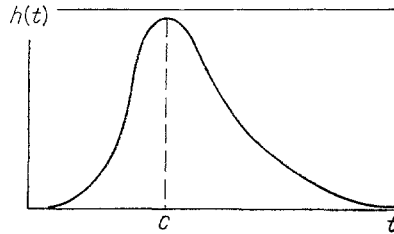


Fig. 1. Variation in concentration h of tracer with time t at the exit from the porous medium.

then the curve $Y(t)$ for the pipes along. Then curve $X(t)$ characterizing the broadening produced by the specimen along is given by

$$X(t) = F^{-1} \left\{ \frac{F[Z(t)]}{F[Y(t)]} \right\}, \quad (4)$$

where F is a forward Fourier transformation and F^{-1} is an inverse transformation.

There are different analytic expressions for the rising and falling branches of the curve, so these parts are considered separately.

The rising branches of the $Z(t)$ and $Y(t)$ curves are approximated by (1), whose Fourier transform is

$$h(v) = a \sqrt{\frac{\pi}{b}} \exp \left(-i2\pi vc - \frac{\pi^2 v^2}{b} \right).$$

From (4) we get the rising branch of $X(t)$ as

$$X(t) = a \exp[-b(t-c)^2],$$

where

$$a = \frac{a_1 b_2}{a_2 \sqrt{\pi(b_2 - b_1)}}; \quad b = \frac{b_1 b_2}{b_2 - b_1}; \quad c = c_1 - c_2.$$

Subscript 1 relates to $Z(t)$ and subscript 2 to $Y(t)$.

At large times, the contribution from the first term in (2) becomes small and the tail on the descending branch is described by the second term:

$$h(t) = d \exp(-\gamma t). \quad (5)$$

We repeat the procedure of (4) to get (5) for the tail of $X(t)$ with the coefficients

$$d = \frac{d_1 \gamma_2}{d_2 \sqrt{\pi(\gamma_2 - \gamma_1)}}, \quad \gamma = \frac{\gamma_1 \gamma_2}{\gamma_2 - \gamma_1}.$$

Knowing a , b , c , d , and γ and using (3) we can derive the parameters of the stagnant zones:

$$\alpha = \frac{100}{1 + \gamma c + \frac{a}{d} \gamma^2 c \sqrt{\frac{\pi}{b}}},$$

$$p = \frac{\gamma}{2bc^2 d \left(1 + \frac{a}{d} \gamma \sqrt{\frac{\pi}{b}} \right)},$$

$$\frac{p}{q} = \frac{1}{2bc^2 \left(1 + \frac{a}{d} \gamma \sqrt{\frac{\pi}{b}} \right)},$$

$$l = \frac{L}{2bc^2}.$$

The method was implemented with the conductivity detector from an LKhM-72 chromatograph. The rock specimen of diameter 22 or 26 mm and length 30-40 mm was placed in a core holder, with lateral hydraulic compression to eliminate gas leakage. A tracer of air of volume 0.05

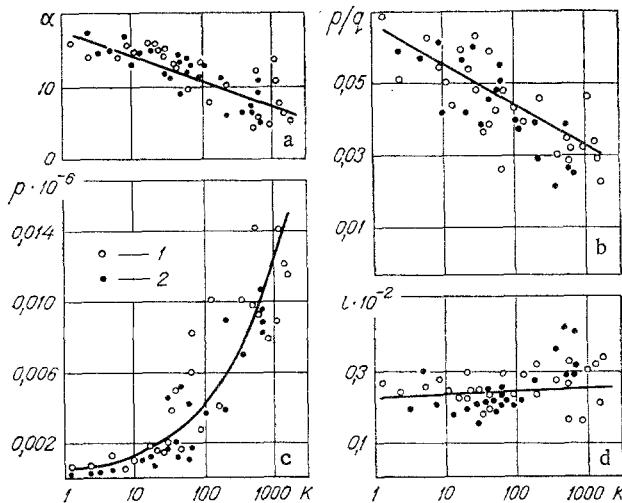


Fig. 2

Fig. 2. Dependence on the permeability K (mD) for the following rocks: 1) terrigenous; 2) carbonate for: a) percentage of stagnant zones α ; b) transfer coefficient p/q ; c) transfer rate p , m^3/sec ; d) cell length l , m.

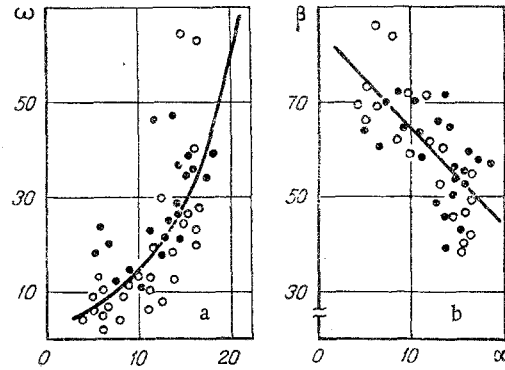


Fig. 3

Fig. 3. Dependence on α (%) of a) residual water content ω in %; b) displacement coefficient β in % (symbols as in Fig. 2).

ml was introduced into the helium flowing through the specimen, and the time course of the concentration at the output was measured. All the experiments were performed with a constant pressure difference of $\Delta P = 10^4 \text{ N/m}^2$.

The use of high pressures increases the relative error of measurement, since it reduces the time for the label to pass although the error of time measurement remains constant (0.2 sec). However, lower pressures result in increased run times and increase in the error associated with the analysis of the tail, whose height is reduced.

The coefficient of variation associated with the error in measuring the time parameters was not more than 2% for specimens varying in permeability from 1.3 to 1500 mD. The time required to analyze and calculate the parameters of the zones in one specimen was not more than 2.5 h.

In all we examined 53 specimens, of which 26 were sandstones and the rest were carbonate rocks from Lower and Middle Carboniferous productive horizons in various deposits in the Perm region. The range in permeability for the terrigenous specimens was 1.3–1576.0 mD, as against 1.3–660.8 mD for the carbonates.

These tests gave α , p/q , p , and l as functions of the permeability (Fig. 2). All the rocks were collectors of pore-space type, and there were no substantial differences between the terrigenous and carbonate ones. The proportion of stagnant zones decreased as the permeability rose (Fig. 2a), and at the same time the rate of exchange with the flow channels increased (Fig. 2c). In the first case the relationship is

$$\alpha = -3.909 \lg K + 18.685,$$

where K is the permeability coefficient in mD, while in the second we have the very much more rapid increase

$$\ln p = 1.245 \lg K - 8.052.$$

Although there is considerable increase in p , p/q decreases, because the speed in the flow channels increases more rapidly for $\Delta P = \text{const}$ than does the rate of exchange between the dead zones and the flow channels.

The length of an ideal-mixing cell hardly varies with the permeability for the terrigenous rocks (correlation coefficient $R = 0.17$), but there is a slow increase with the permeability for the carbonate rocks (correlation coefficient $R = 0.59$).

There is also a relation between α and the residual water content or the displacement coefficient. The corresponding equations are

$$\ln \omega = 0.141\alpha + 1.251, \quad \beta = -2.069\alpha + 84.530,$$

where $R = 0.74$ and $R = -0.71$, respectively. The residual water content increases with the proportion of stagnant zones (Fig. 3a), while the displacement coefficient decreases (Fig. 3b).

NOTATION

t , time; h , tracer concentration; L , length of porous medium; q , volume flow rate in channels; α , stagnant zones; u , linear flow velocity in channels; P , pressure; i , imaginary unit; ω , residual water content; β , displacement coefficient.

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SIMULATION OF MASS-EXCHANGE PROCESSES IN A MASS-DIFFUSION SEPARATING ELEMENT

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We obtain a system of nonlinear algebraic equations which can be used for calculating the working and separating characteristics of a mass-diffusion element.

The mass-diffusion method has been used for a relatively long time in the production of inert-gas isotopes, but the theory of a separating element has not been adequately worked out up to now, so that it is impossible to design the apparatus in an optimum manner.

In [1] we showed that the fundamental separating characteristics of a mass-diffusion element, ϵ and L' , are determined by its internal working parameters $\ln q$ and θ_v . These two parameters were considered to be independent in [1], which enabled us to analyze their effect on ϵ and L' over wide ranges; however, in a real apparatus a connection between them exists and must be taken into account.

Taking account of such a connection is possible only on the basis of a consideration of a model which will describe the diffusion and hydrodynamic processes taking place in a separating element of a specified design. In this consideration, the only independent parameter will be Q_0 . All other quantities, both internal ($\ln q$, θ_v) and external (ϵ , L') must be determined by solving the problem simultaneously as a function of Q_0 .

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