

DISPERSION COEFFICIENT WITH THE DISPLACEMENT OF
A GAS FROM A POROUS MEDIUM BY A GAS

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The article gives the dependence of the dispersion coefficient on the Péclet number, obtained with the analysis of experimental data on the displacement of a gas by a gas from a porous medium of varying permeability.

The displacement of a gas by a gas from a porous medium takes place in many industrial processes, in particular, with the exploitation of gas-condensate deposits by the return injection of a dry gas (the cycling process). The physical picture of the displacement of a gas by a gas from a porous medium is in many ways analogous to mixing of liquids by displacement, but may differ considerably with respect to quantitative parameters, since the diffusion coefficient of the gas with normal pressure is four orders of magnitude and at the stratum pressure two orders of magnitude, greater than the diffusion coefficient of liquids.

The dependence of the dispersion coefficient with the mixing of liquids by displacement on various factors is considered in connection with the need to determine the size of the zone of the mixture with the exploitation of petroleum deposits.

A great number of experimental data have been correlated and represented in the form of the dimensionless dependence [1, 2]

$$\frac{D}{D_0} = \frac{1}{E} + \varphi \left(\frac{du}{D_0} \right)^n, \quad (1)$$

where D is the dispersion coefficient; D_0 is the coefficient of molecular dispersion; u is the filtration rate; d is the mean particle size of the porous medium, E is the coefficient of tortuosity; φ , n are coefficients, depending on the character of the porous medium and its homogeneity.

A graphical representation of the dependence $D/D_0 = f(du/D_0)$ permits separating out a region where molecular diffusion is determining ($D/D_0 = \text{const}$) and a region of convective mixing ($du/D_0 \geq 10^{-1}$) where $D/D_0 \sim u^n$.

Experiments with different porous media have shown that the coefficients in Eq. (1) can fluctuate over very wide limits. For example, the coefficient of tortuosity for a majority of free-flowing media $E = 1.5$; for some sandstones, dolomites, and limestones, it rises to 10 or more [3]. This means that, in the region of molecular diffusion, the calculated estimate of the dispersion coefficient can lead to an error of 10 times, and in evaluation of the length of the zone of the mixture, by 3 times. According to the data of [1], the power exponent in Eq. (1) fluctuates within the limits 1.17-1.24, and, according to the data of [4], $n = 1.0-1.5$, i.e., the error in evaluation of the coefficient in the region of convective dispersion, for example, with $du/D_0 = 10^1$, can increase by 3 times. Such a large difference in the dispersion coefficients for exactly the same Péclet numbers du/D_0 is generally explained by the factor of the inhomogeneity of the porous media. With a significant level of the values, a calculated evaluation of the dispersion coefficient and the length of the zone of the mixture is difficult due to the low accuracy.

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TABLE 1

Gases	D_0 cm ² /sec
N ₂ -CO ₂	0,158
N ₂ -Ar	0,191
CH ₄ -Ar	0,200

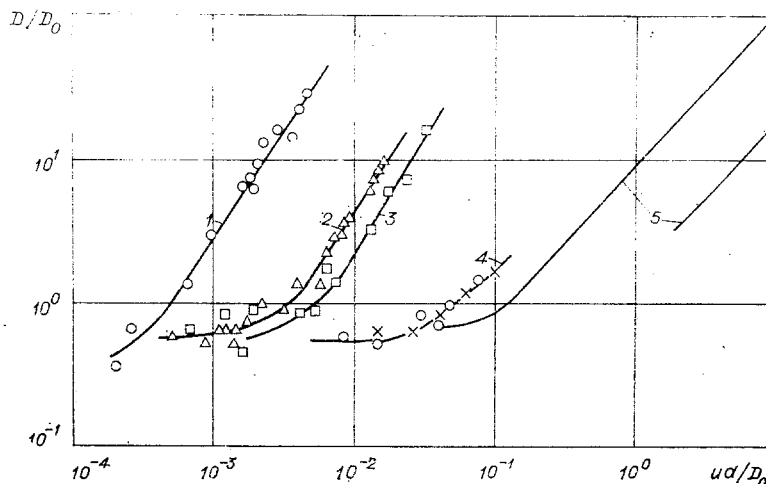


Fig. 1

The dispersion coefficient with displacement of a gas from a porous medium by a gas has been insufficiently studied experimentally. The results of only one experiment are known [1], which was carried out in a medium with a high porosity ($k = 15$ g) in the region of the prevailing effect of molecular diffusion, coinciding with the generalized dependence for liquids. It was assumed that this dependence is valid also for the region of convective mixing.

The results of experiments on the displacement of a gas from a porous medium by a gas, undertaken to study the special characteristics of this process, are set forth below.

The investigation of the displacement of a gas from a porous medium by a gas was carried out in tubes with diameters of 50 and 35 mm and lengths of 2 and 3 m, filled with quartz sand of different fractional composition. The permeability of the samples $k = 23, 12$ g; 400, 128, and 18 mg. In a majority of the experiments, nitrogen was displaced by carbon dioxide gas. The composition of the gas mixture at the outlet from the tube was determined by analysis of samples in a VTI-2 gas analyzer, which works on the principle of the absorption of carbon dioxide by a solution of potassium hydroxide.

A certain number of the experiments were made with the displacement of argon by nitrogen, and of nitrogen or argon by methane. In this case, the composition of the gas mixture at the outlet was determined by a chromatograph. The gas entered the tube from cylinders through a regulator, maintaining a constant pressure. At the outlet from the tube, two successive regulating valves permitted a previous selection of the desired mass flow rate of the gas. Beyond these valves, glass pipettes were mounted in series for withdrawing samples, followed by a gas counter. The pressure of the gas in the pipelines of the unit and at various points of the tube was measured by standard manometers.

The principal experiments consisted in determination of the amount of gas extracted from the samples and its composition at the outlet with a constant pressure at the inlet ($p = 15-2$ atm), for different filtration rates. The experiments were carried out in such a way that, with fully established filtration conditions of one gas, the valve in the supply line was closed, and, simultaneously, the valve in the feed line of the displacing gas, whose pressure was previously established as equal to the pressure of the displaced gas, was opened. The moment of the switching-on of the feed of gas was taken as the starting moment of the displacement experiment. The results of each experiment were used to construct the dependence of the change in the concentration of the displacing gas with time. This dependence was used to determine the dispersion coefficient in accordance with the Khierichi formula [5], which was obtained by solution of a differential equation with a convective term, with a probability distribution of the concentration

$$D = \frac{1}{T} \left(u \frac{t_2 - t_1}{3.625} \right)^2,$$

where t_1 , T , t_2 are the times from the start of the experiment up to the moment of the attainment of concentrations of 10, 50, and 90%.

Samples with a permeability $k = 23$ and 12 g were filled with quartz sand with a fractional composition of 0.2-0.25 and 0.1-0.2 mm; to determine the Péclet number, the mean value of the diameter of the particles was taken as $d = 2.25 \cdot 10^{-2}$ and $1.5 \cdot 10^{-2}$ cm.

For samples filled with sand of a broad fraction ($k = 18, 128, \text{ and } 400$ mg), the mean diameter of the particles was arbitrarily defined with respect to the permeability k and the porosity.

The mean diameter of the particles was computed using the formulas of Kozeny, Terzaghi, and Uren [6], while the experimental coefficients in them were previously determined from data for samples filled with sand of known fractional composition [1, 2]. Calculations using the three formulas give close values of the mean arbitrary diameter of the particles, which, for the given samples, were taken equal to $0.9 \cdot 10^{-3}$, $2.3 \cdot 10^{-3}$, and $4.35 \cdot 10^{-3}$ cm. The inaccuracy in determination of the mean arbitrary diameter of the particles of the porous medium can have an effect on the value of the Péclet number, but not on its order of magnitude.

The coefficients of molecular diffusion for the different pairs of gases used in the experiments, at a pressure of 1 atm and a temperature of 15°C, are given in Table 1 [7]. The coefficient of molecular diffusion of the gases was computed using the dependence $D_0P = \text{const}$.

The results of the analysis of experiments on the displacement of a gas by a gas from samples of different permeability are shown in Fig. 1 (for $k = 18; 128; 400$ mg and $12; 23$ g, curves 1-4, respectively). For purposes of comparison, the same figure gives plots of generally known experimental dependence, obtained with displacement by the mixing of liquids [1] (curve 5).

It is worthy of note that the change in the character of the dependence of the relative dispersion coefficient as a function of the Péclet number, i.e., the boundary between the regions of molecular diffusion and the predominant effect of convective mixing, with displacement of a gas by a gas depends on the permeability of the porous medium. While for readily permeable porous media ($k = 29$ and 12 g) this boundary corresponds to Péclet numbers $ud/D_0 \approx 10^{-2}$, which is in agreement with the dependence for displacement by the mixing of liquids, for media with a relatively low permeability this boundary is shifted into the region of Péclet numbers 10^{-3} (for $k = 128$ and 400 mg) and even 10^{-4} (for $k = 18$ mg).

The increase in the dispersion coefficients with the filtration rate for the three low-permeability samples takes place at approximately the same rate, and the power exponent in Eq. (1), determined using the dependence given in Fig. 1, is evaluated by the value $n = 1.5$.

The stratification of the experimental curves in Fig. 1 for samples of different permeability may be the consequence of a certain arbitrariness in determination of the Péclet number from the arbitrary diameter of the particles, without taking account of the character of the packing, the inhomogeneity factor, and other special characteristics of the porous medium. However, a tendency toward an increase in the dispersion coefficient with a decrease in the mean diameter of the particles with identical Péclet numbers is not in doubt. This experimental fact has been noted earlier [8].

In the region of a predominant effect of molecular diffusion, values of $D/D_0 = 0.5-0.6$ are obtained, and not the values of $D/D_0 = 1/E = 0.7$ generally given in the literature for porous media with a high porosity.

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