

## GAS MIXING IN LABORATORY CORES

Представлены результаты экспериментов по замещению метан-углерода в лабораторных условиях. Математическая модель описывает массоперенос в отношении сжимаемости газа и изменяющейся скорости потока. На основе модели определены коэффициенты депрессивности и молекулярной диффузии.

This paper presents the results of methane-nitrogen displacement experiments in a laboratory core. Mathematical model describing transport of mass with respect of gas compressibility and variable flow velocity has been presented. On the basis of this model the dispersivities and the molecular diffusion coefficients have been determined.

### Introduction

The problem of gas displacement in porous media has essential meaning in underground gas storage especially in the presence of inert gasses. In the process of gas-gas displacement in porous media the displacing gases are separated by mixing zone of changing composition in which both gases are present. The size and extent of this mixing zone depends on many superimposing effects such as: molecular diffusion, heterogeneity of the porous media, turbulence of flow, viscous fingering, adsorption/desorption, stagnant fraction of pore space, presence of immobile fluid etc. The cumulative effect of all such factors is referred as dispersion which is characterized by molecular diffusion and dispersivity [1], [4], [5]. These are usually determined by the analysis of the displacement experiments but most authors usually make assumption of constant interstitial velocity. In general this assumption is valid for incompressible liquid flow but not in the case of flow of gases. In this paper the mathematical model of miscible displacement of two different gases in porous media with variable flow velocity has been presented. The results of the experiments have been performed and the coefficients of molecular diffusion and the dispersivities have been determined.

### Mathematical model of gas displacement in porous media

When one fluid miscibly displacing another in a linear porous medium and when the

displacement is stable so that viscous fingering do not form, the following convection-dispersion equation is often used to describe the displacement. This equation is [2], [3]:

$$K(t) \frac{\partial^2 C(x,t)}{\partial x^2} - u(t) \frac{\partial C(x,t)}{\partial x} = \frac{\partial C(x,t)}{\partial t} \phi, \quad (1)$$

where  $C(x, t)$  – concentration of displacing fluid;  $K(t) = D_M + \beta u(t)$  – dispersion coefficient [ $\text{m}^2/\text{s}$ ];  $D_M$  – molecular diffusion coefficient [ $\text{m}^2/\text{s}$ ];  $\beta$  – dispersivity [ $\text{m}$ ];  $u(t)$  – superficial velocity (Darcy velocity) [ $\text{m/s}$ ];  $\phi$  – porosity.

Often in the laboratory experiments the gas with the concentration  $C = 0$  flows through a column filled with porous medium. At  $t = 0$  the second gas with constant concentration  $C = 1$  is introduced at the inlet, at  $x = 0$ . Subsequently the effluent concentration  $C(x, t)$  is measured at the outlet  $x = L$ . The boundary and initial conditions appropriate for this case are [1], [6]:

$$\begin{aligned} C(x, 0) &= 0 \quad \text{for } x > 0, \\ C(0, t) &= 1 \quad \text{for } t \geq 0, \\ C(x, t) &= 0 \quad \text{for } x \rightarrow \infty. \end{aligned} \quad (2)$$

The solution of convection-dispersion equation (1) with the boundary and initial conditions (2) for constant interstitial velocity is [1], [4]:

$$C(x,t) = \frac{1}{2} \left[ \operatorname{erfc} \left( \frac{x - \frac{u}{\phi} t}{2 \sqrt{\frac{K}{\phi} t}} \right) + \exp \left( \frac{\frac{u}{\phi} x}{\frac{K}{\phi}} \right) \operatorname{erfc} \left( \frac{x + \frac{u}{\phi} t}{2 \sqrt{\frac{K}{\phi} t}} \right) \right], \quad (3)$$

where  $\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$ , and  $\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-u^2) du$  is an error function.

In this paper in order to determine the molecular diffusion coefficients and dispersivities the approximate solution of equation (1) for variable flow velocity proposed by [6] has been used. This solution reads:

$$C(x,t) = \frac{1}{2} \operatorname{erfc} \left( \frac{x - x_f(t)}{\frac{2}{\sqrt{\phi}} \sqrt{D_M t + \beta \phi x_f(t)}} \right). \quad (4)$$

In this approach the total mass-transport is a superposition of the convective transport and the dispersion transport taking place near the displacement front  $x_f(t)$ . The displacement

front here is considered as a hypothetical boundary which would have existed between the gases if they had not mix with each other. The position of displacement front  $x_f(t)$  can be evaluated on the basis of the material balance as:

$$x_f(t) = \frac{Bg(p_{av}(t))}{A\phi} \int_0^t q(\tau) d\tau, \quad (5)$$

where  $A$  – cross sectional area of the core [m<sup>2</sup>];  $p_{av}$  – average pressure in the core [Pa];  $q$  – volumetric flow of displacing gas [m<sup>3</sup><sub>n</sub>/s];  $Bg$  – gas formation volume factor.

### Laboratory apparatus and operating procedures

Fig.1 is a schematic diagram of the gas mixing measurement apparatus. The measurement is realized as follows: methane from high pressure gas cylinder – 1 flows through the flow controller – 2 where the constant volumetric flow is adjusted and then flowing through the core – 3 displaces nitrogen from it. The effluent concentration of displacing gas (methane) is measured at the outlet of the core by the infrared methane detector Polytron Ex – 4. During the experiment parameters like: temperatures and pressures at the inlet and the outlet of the core are measured as well. All measured parameters are recorded in microprocessor recorders: DDL/12S/220, DDL/12S/24 – 5 and 6.

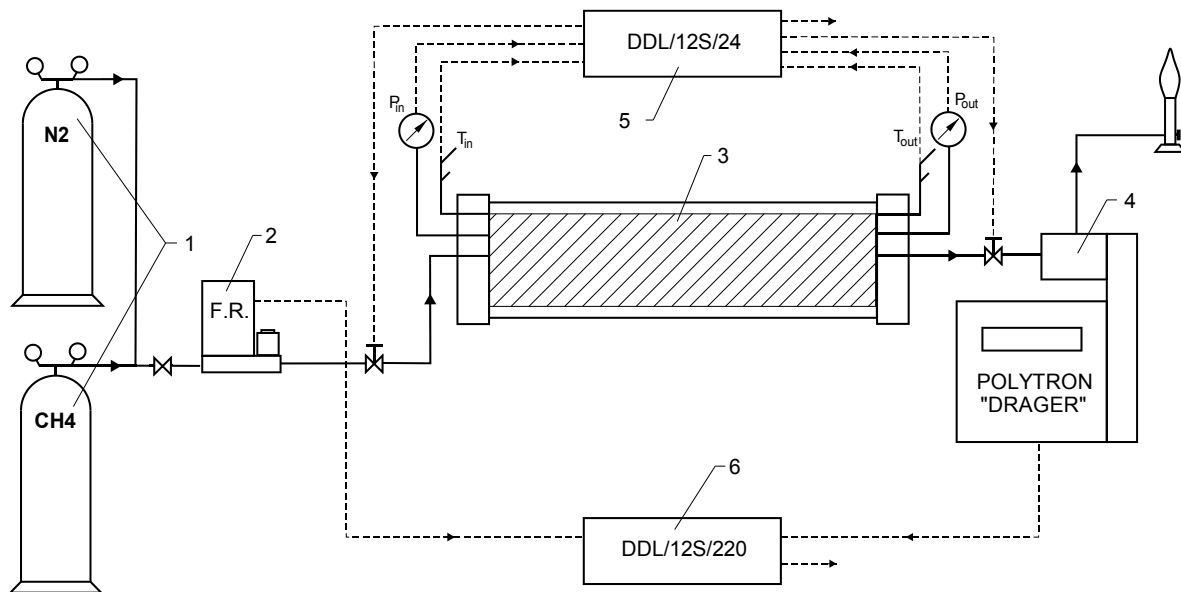


Fig.1. Experimental apparatus

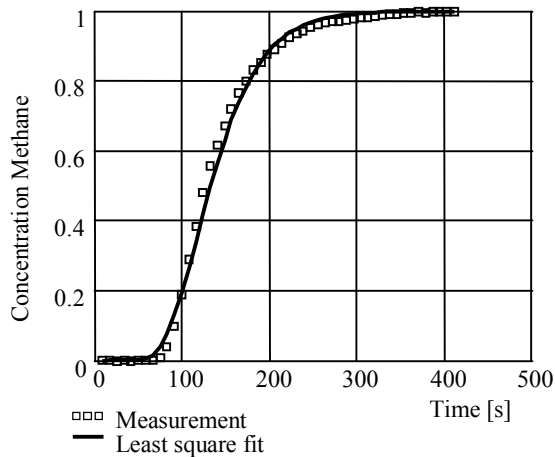


Fig.2. Breakthrough curve for a methane/nitrogen displacement

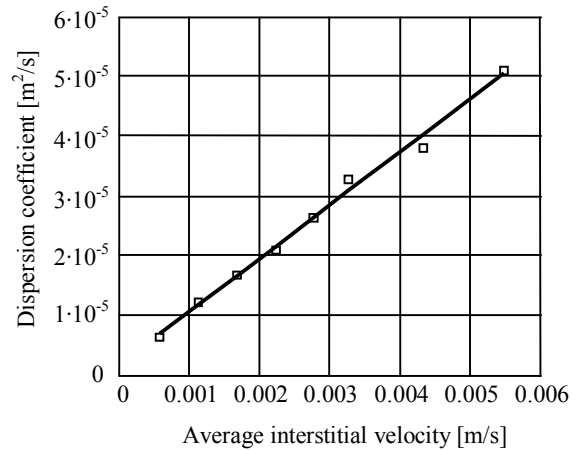


Fig.3. Dispersion coefficient versus average interstitial velocity

### Experimental results and data analysis

Eight series of experiments were conducted during the methane/nitrogen displacement in a sandstone core with different flow rates ranged from 10 to 100 ml/min (measured at 293 K and 1 atm) at the low pressures close to atmospheric. Physical properties of the core are shown in table 1. Gas properties at 1 bar and 273 K are listed in table 2.

Tab.1

#### Core properties

Length [m]	Cross Sectional Area [m <sup>2</sup> ]	Porosity [-]	Permeability [md]
0.57	11.83·10 <sup>-4</sup>	0.271	824

Tab.2

#### Gas properties

Gas	Viscosity [Pa·sec]	Density [kg/m <sup>3</sup> ]	Compressibility factor
Methane	11.46·10 <sup>-6</sup>	0.651	0.998
Nitrogen	17.70·10 <sup>-6</sup>	1.135	1

Figure 2 illustrates a typical effluent concentration profile (breakthrough curve) for a methane/nitrogen displacement with a fit to the dispersive model (4). Dispersivities and molecular diffusion coefficients for all experiments because of variable flow velocity were found with the use of nonlinear optimization methods by minimization of the functional:

$$\Theta(D_{M_i}, \beta_i) = \sum_{i=1}^N \sum_{j=1}^{W_i} [C^{(i)}(D_{M_i}, \beta_i, t_j) - C_j^{(i)}]^2 = \min \quad (6)$$

with constraint

$$D_{M_1} / D_{M_i} = p_i / p_1 \text{ and } i = 1 \dots N,$$

where  $C_j^{(i)}$  – methane effluent concentration for  $i$  – series at time  $t_j$ ;  $W_i$  – sample size for  $i$  – series;  $N$  – number of measurement series.

Calculations were made with the use of author's program written in MathCad 2000 with the use of nonlinear regression methods. The results are shown in table 3.

Tab.3

#### Calculated parameters of dispersive model

Average Interstitial Velocity [m/s] 10 <sup>-4</sup>	Pressure [Pa] 10 <sup>5</sup>	Molecular Diffusion Coefficient [m <sup>2</sup> /s] 10 <sup>-6</sup>	Dispersivity [m]	Goodness of Fit R <sup>2</sup> [-]
5.70	0.995	1.274	0.033	0.998
11.2	1.017	1.247	0.036	0.997
16.6	1.019	1.244	0.035	0.995
22.1	1.016	1.248	0.033	0.996
27.5	1.023	1.239	0.034	0.995
32.6	1.029	1.232	0.036	0.998
43.2	1.046	1.212	0.033	0.997
54.6	1.060	1.196	0.034	0.998

As it is seen from table 3 molecular diffusion coefficient decreases with increase of pressure whereas mechanical dispersivity changes slightly with average value 0.034 m. Fig.3 shows the dispersion coefficients against average interstitial velocity. As is shown with an increase of flow velocity the dispersion coefficient increases linearly.

### Summary

In this paper a method of the interpretation of gas-gas displacement in porous media with respect of variable flow velocity has been presented. The coefficients of molecular diffusion and the dispersivities with the use of nonlinear optimization methods have been determined. This method allows to reduce the effect of the dependency of the parameters (molecular diffusion and dispersivity). This in turn allows for the simultaneous determination of the molecular diffusion coefficient and the dispersivity and consequently determination the intensity of gas mixing in a porous medium in laboratory scale.

### LITERATURE

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