

DETERMINATION OF DISPERSION COEFFICIENT IN CARBONATE ROCK USING COMPUTED TOMOGRAPHY BY MATCHING IN SITU CONCENTRATION CURVES

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ABSTRACT

Dispersion coefficient is an important parameter for the modeling of multiphase flow in reservoirs, particularly in the case of miscible displacements. It accounts for hydrodynamic mixing that occurs in porous media, as a result of fluid flow through the channels connected and distributed in random directions. The present paper deals with laboratory measurement of dispersion coefficients when displacing miscible fluids in carbonate rocks. The focus is on the methodology for determining the in-situ saturation along the sample and the subsequent data treatment for the rendering of the controlling parameters. The target was the dispersion coefficient between two aqueous phases bearing different salinities. In-situ saturations were obtained via X-Ray Computed Tomography (CT). Displacement tests were carried out by injection of NaI brine solutions into the rock sample once saturated with a NaCl brine, followed by a reverse injection cycle. The rock sample consisted of a clean limestone core, 5 cm in diameter and 77.2 cm long, retrieved from an outcrop in NE Brazil (Morro do Chaves formation). The deposition of limestone formed by bivalves and shales are essentially rich of organic plant fragments, fish remains and ostracods [1]. Variations in the injection rate were carried out to observe the effect in the dispersion coefficient. The data rendered by the CT scans allowed the calculation of in-situ concentration distributions for different instances of the displacement and to identify the presence of heterogeneities in porous media. In situ concentration history profiles were best-fitted to convection-dispersion models (with and without retardation effects) using a nonlinear regression method. The global fitting process, considering all the historic distribution data, was used to calculate dispersion coefficient. The amount of data used and the proved robustness of the method allowed a very good model fit to the experimental data. In the end, it rendered a dispersion coefficient of 0.02 cm²/s and 0.09 cm²/s for 1 cm³/min and 5 cm³/min flow rate, respectively.

INTRODUCTION

Application of improved recovery methods to be applied in heterogeneous carbonate reservoirs represents currently a major challenge in the petroleum industry. The complex

nature of carbonates hampers the characterization of the reservoir properties such as porosity, permeability and hydrocarbon saturation. The pore structure of the carbonate reservoir rocks poses a great difficulty in the prediction of the fluid flow behavior in porous media. Dispersion coefficient is an important parameter to characterize the fluid flow in miscible recovery methods [2, 3].

The dispersion coefficient describes the multiphase flow in oil reservoirs, especially at miscible displacement conditions. If a solution is injected into a saturated porous rock, solute moves through the flow channels of the medium at different speeds, depending on the size and shape of the pore channels [4].

Typically, the dispersion coefficient is obtained by adjusting the production curve by means of the convection-dispersion equation (CDE). The production curve is obtained from a displacement experiment, in which two miscible fluids flow through the porous media and the concentration of the effluent is measured at the outlet of the sample as a function of time [5]. Recently, X-ray computerized tomography (CT) has been applied as a nondestructive technique to monitor the flow of fluid through the rock and to determine the fluid saturations, allowing to visualize the effects of fluid viscosity and density on the flow [6, 7].

Peters et. al. [8] presented a method to measure the longitudinal dispersion coefficient and adsorption in porous media by X-ray computed tomography. The concentration profiles inside the porous media were adjusted by a mathematical model of convection - dispersion. Fourar et. al. [9] carried out CT tests using tracers over several carbonate samples in order to improve the interpretation of dispersion in heterogeneous porous media. The results showed that the dispersion coefficient is not kept constant along the sample distance.

This work determined the dispersion coefficient for the brine flow in carbonate rock samples at two brine concentrations. Dispersion is measured during the flow mixing process for different concentrations of brine. Salt concentration distributions were obtained through computerized tomography images. The concentration profiles of the tests were analyzed by means of convection-dispersion models and parameters were determined via optimization by a nonlinear least square Gauss-Maquardt method.

METHOD

Theory

The dimensionless dispersion-convection equation is defined as

$$\frac{\partial C_D}{\partial t_D} + \frac{\partial C_D}{\partial x_D} - \frac{1}{N_{Pe}} \frac{\partial^2 C_D}{\partial x_D^2} = 0 \quad (1)$$

According to Brigham [10] model, the boundary conditions for the salt concentration inside the porous medium is given by

$$C_D(x_D, 0) = 0 \quad t_D = 0, \quad C_D(0, t_D) = 1 + \frac{1}{N_{Pe}} \frac{\partial C_D}{\partial t_D} \quad x_D = 0, \quad C_D(\infty, t_D) = 0 \quad x_D = \infty$$

By these boundary conditions, the analytical solution for the CDE model for the salt concentration inside the porous medium is:

$$C_D = \frac{1}{2} \operatorname{erfc} \left(\frac{x_D - t_D}{2\sqrt{t_D/N_{Pe}}} \right) + \frac{t_D}{\sqrt{\pi \cdot t_D/N_{Pe}}} \cdot \exp \left[- \left(\frac{x_D - t_D}{2\sqrt{t_D/N_{Pe}}} \right)^2 \right] - [N_{Pe}(x_D + t_D) + 1] \cdot \frac{1}{2} \cdot \exp(N_{Pe} \cdot x_D) \cdot \operatorname{erfc} \left(\frac{x_D + t_D}{2\sqrt{t_D/N_{Pe}}} \right) \quad (2)$$

Where $N_{Pe} = v \cdot L / K_l$, N_{Pe} is the Peclet Number, v is the interstitial velocity (cm/s), L is sample length (cm), K_l is the dispersion coefficient (cm^2/s), t_D is the dimensionless time, x_D dimensionless length and C_D is the dimensionless concentration.

The CDE model was later extended by the addition of the Retention Factor (R_f) which represents the fluid-rock interactions.

$$R_f \frac{\partial C_D}{\partial t_D} + \frac{\partial C_D}{\partial x_D} - \frac{1}{N_{Pe}} \frac{\partial^2 C_D}{\partial x_D^2} = 0 \quad (3)$$

R_f is the Retention factor. Shukla et al [11] presented a mathematical analytical solution for the Eq (3). Changes were made here for keeping the same nomenclature:

$$C_D = \frac{1}{2} \operatorname{erfc} \left[\left(\frac{N_{Pe}}{4 \cdot R_f \cdot t_D} \right)^{\frac{1}{2}} \cdot (R_f \cdot x_D - t_D) \right] + \left(\frac{t_D \cdot N_{Pe}}{\pi \cdot R_f} \right)^{\frac{1}{2}} \cdot \exp \left[- \left(\frac{N_{Pe}}{4 \cdot R_f \cdot t_D} \right) \cdot (R_f \cdot x_D - t_D)^2 \right] - \left[N_{Pe} \cdot x_D + \frac{N_{Pe}}{R_f \cdot t_D} + 1 \right] \cdot \frac{1}{2} \cdot \exp(N_{Pe} \cdot x_D) \cdot \operatorname{erfc} \left[\left(\frac{N_{Pe}}{4 \cdot R_f \cdot t_D} \right)^{\frac{1}{2}} \cdot (R_f \cdot x_D + t_D) \right] \quad (4)$$

Calculation

The calculation procedure for determining the parameters involved in the mentioned models is summarized in Figure 1.

Experimental Procedure

Tests were conducted by the injection of a NaI aqueous solution into the rock saturated with an NaCl aqueous solution and vice-versa. The producing mass flow was monitored

by a digital scale installed in the outlet line. The injection was provided by a positive displacement pump operated at constant flow. Four tests were performed in two different injection flow rates. The most relevant experimental settings are shown in Table 1.

RESULTS

The results obtained for the model without retention are displayed in Table 2. As observed, the higher the interstitial velocity, the higher the dispersion coefficient. Tests 1 and 2 show larger square errors compared with tests 3 and 4. Test 1 and 3 were made on the same experimental settings, except for the overburden pressure that was 2,000 psi for Test 3. It was observed that results from lower pressure tests allowed a better fit of the model to the experimental data. In addition, a lower overburden pressure yielded slightly higher values for the dispersion coefficient; however the pressure has a smaller effect on the dispersion coefficient than that caused by the velocity changes.

Figure 2a shows the adjust for Test1 data, which is evidently of low quality. It indicates that the model is missing some important phenomena. Table 3 presents the results obtained by applying the model including the retention factor. The data fit yielded the same values for dispersion coefficient for all experiments. This observation allows us to conclude that the models do not have inconsistencies that could arise due to intrinsic errors arising from the determination of the fluid concentrations at the outlet against those inside the sample, as well as from the selection of initial and boundary conditions.

The experimental retention factors obtained were less than one, showing that a certain amount of the liquid phase does not participate in the transport process. This is probably due to the presence of heterogeneities in the porous media which produce fluid trapping, turning part of the fluid motionless. It is possible to observe that when considering the adsorption process the model with retention presents an improvement over the previous model, which can be seen in Figure 2b.

CONCLUSIONS

- A method was developed to determine the dispersion parameters honoring all the in-situ concentration data rendered by CT image scans, via an optimization procedure for the best-fit parameters.
- The method was applied successfully for the determination of the dispersion coefficient in the displacement of brines in a carbonate rock.
- Results confirmed that the dispersion coefficient is directly proportional to the mean velocity and that overburden pressure has a slight effect on the dispersion coefficient.

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Table 1. Experimental conditions.

LIMESTONE							
Diameter (cm)	4.8	Length (cm)	77.2	ϕ (%)	14	k_w (mD)	30.38
FLUIDS: BRINES							
NaI Sol.		100g/L NaI		NaCl Sol.		50g/L	
ρ (g/cm ³)		1.06		ρ (g/cm ³)		1.02	
EXPERIMENTAL CONDITION							
TEST - 01		TEST- 02		TEST- 03		TEST- 04	
NaI-Injection		NaCl-Injection		NaI-Injection		NaCl-Injection	
v(cm/s)	0.00647	v(cm/s)	0.03361	v(cm/s)	0.00670	v(cm/s)	0.03432
$P_{\text{overpressure}}$ (psi)	5,000	$P_{\text{overpressure}}$ (psi)	5,000	$P_{\text{overpressure}}$ (psi)	2,000	$P_{\text{overpressure}}$ (psi)	2,000

Table 2. Results from models without retention

Test	N_{Pe}	K_1 (cm ² /s)	Square Error
1	32.89	0.0157	2.98
2	27.68	0.0933	1.65
3	26.53	0.0195	0.88
4	29.91	0.0877	0.62

Table 3. Results from models with retention included.

Test	N_{Pe}	K_1 (cm ² /s)	R_f	Square Error
1	32.04	0.0156	0.89	0.56
2	27.75	0.0931	0.92	0.49
3	26.74	0.0194	0.95	0.54
4	29.54	0.0888	0.97	0.49

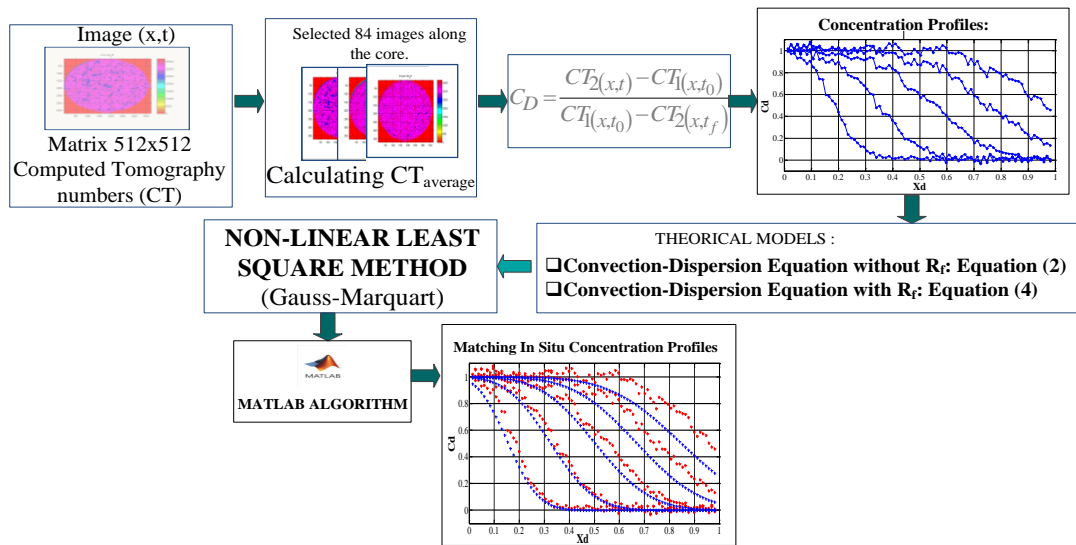


Figure 1. Calculation procedure for models without and with retention.

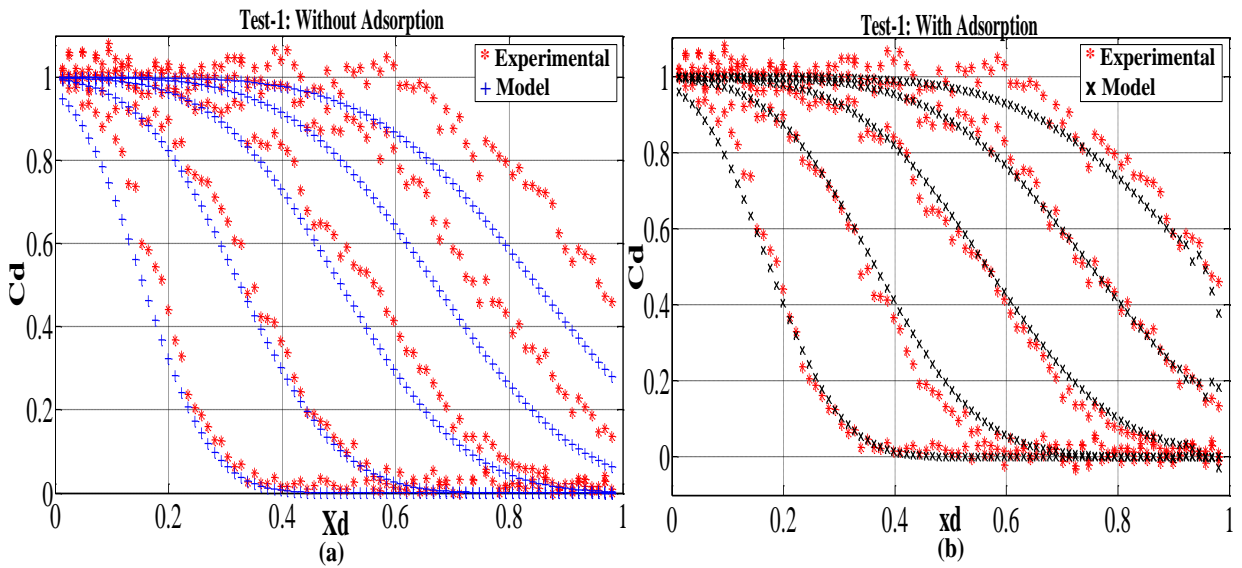


Figure 2. Concentration profile for models without and with adsorption.