

# TRACER DISPLACEMENTS FOR EOR EXPERIMENTS: THEORY, MODELING, AND EXPERIMENTS.

Roland Lenormand, Guillaume Lenormand and Fabrice Bauget  
Cydarex

*This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in St. John's Newfoundland and Labrador, Canada, 16-21 August 2015*

## ABSTRACT

During Enhanced Oil Recovery (EOR) experiments, front spreading is due to various mechanisms: pore-scale mixing, channeling due to permeability heterogeneity, viscous fingering, capillary effects, etc. This paper gives a review of existing models for the simplest case of tracer spreading and a discussion of their validity based on comparison with laboratory experiments.

We first recall the definitions and the physical mechanisms describing pore-scale mixing and spreading, and their modeling at the scale of a Representative Elementary Volume (REV, local or Darcy-scale approach) called "microdispersion". When used as local input in 3-Dimensional (3-D) simulations, the Darcy-scale approach can describe the plug-scale spreading related to permeability heterogeneity. In a 3-D heterogeneous medium, even a displacement started as a piston-type at the Darcy-scale leads to a dispersion behavior. However, laboratory experiments are rarely simulated with 3-D models, but only with 1-D models. A local microdispersion displacement in a 1-D simulation cannot model the large spreading observed at the plug-scale. Consequently, additional parameters must be introduced in 1-D local laws to compensate for the missing information on heterogeneities, and we recall here the existing up-scaled (or homogenized) models (microdispersion, macrodispersion and convective channeling).

These models are compared to our tracer experiments. Displaced and injected fluids have different salinities, and local saturation profiles were measured using ten electrodes along the sample. Our results confirm previously published results that channeling convective models are more suitable than standard dispersion models. The best result is obtained by calculating a permeability distribution function in a stratified model. This model accounts for the long tail in the effluent production and the in-situ concentration profiles.

## INTRODUCTION

During Enhanced Oil Recovery (EOR) experiments, front spreading is due to various mechanisms: pore-scale mixing, channeling due to permeability heterogeneity, viscous fingering, capillary effects, etc.

The main objective of this paper is to clarify the mechanisms linked to the spreading of a tracer in a porous medium and to present the equations used to model the concentration as a function of time and space (transport equation) at the scale of a plug of real rock. We

will show that a transport equation written at the scale of a REV needs to be modified when applied to a plug, due to the presence of heterogeneities. This effect, called homogenization (up-scaling), will be discussed, and existing models will be compared to our experiments. We first give some definitions, then present existing models used at the REV scale, and finally we describe homogenized transport equations.

### Definitions

A “tracer” is a soluble substance, like dye or salt, which at low concentration does not change the fluid properties. “Dispersion” is used as a general term equivalent of spreading, independently of fluids characteristics: miscible or not, with or without viscosity contrasts. Originally “diffusive” spreading was referring to the physical mechanism of molecular diffusion leading to a transport equation with a second order derivative with respect to space. By extension, this term is now generally used when spreading is described by a term of transport equation with a second order spatial derivative, leading to the width of the front being proportional to the square root of the travelled distance, even if the physical mechanism is not molecular diffusion. We will see that an uncorrelated velocity field also leads to a front spreading with square root of travelled distance. When molecular diffusion is negligible, spreading is due to spatial differences in velocities, either at pore level or at larger scale (permeability heterogeneities) and dispersion is called “hydrodynamic” (or advective).

In general, a transport equation in concentration as function of time and distance contains three terms: the transient term with a derivative with respect to time, a term with a first order derivative in space, called the "convective" term, and a term with a second order in space, called the dispersive term.

### Flux and concentration

All the equations are written at the Darcy scale, meaning that a REV of porous medium contains a large number of pores (such as the micromodel in Figure 1).

The tracer “concentration”  $C$  is the mass of tracer per unit volume. The “flux”  $F$  is the mass of tracer crossing a given surface per unit of time. The “flux density”  $f$  is the flux per unit surface.

In an elementary volume (length  $dx$  in the direction of flow, cross-section area  $dA$ , porosity  $\phi$ , and volume  $dV = dA\phi dx$ ), the mass balance equation implies that the accumulation of solute during  $dt$ ,  $dA\phi dx \partial C / \partial t dt$ , is equal to the quantity of tracer entering in  $x$ ,  $dAf(x)dt$ , minus the quantity of tracer leaving the volume,  $dAf(x + dx)dt$ . This leads to the 1-D mass balance equation, valid with no tracer adsorption:

$$\frac{\partial C}{\partial t} + \frac{1}{\phi} \frac{\partial f}{\partial x} = 0. \quad (1)$$

In order to derive the concentration as function of time and distance, the dispersion equation, relating the flux density  $f$  to the concentration  $C$  is required. In addition to the mass balance and the dispersion equation, Darcy's equation is used to calculate the local velocity as function of fluid properties and pressure gradient.

In the following sections, we will study the local dispersion equation for tracer flow. Then we will describe the integration of this local equation for a 2 or 3-D flow, leading finally to the 1-D homogenization, average in a 1-D flow as commonly used to represent laboratory experiments.

### Tracer local equation (Microdispersion)



Figure 1- Tracer flow experiment in a micromodel. The tracer in red is injected at a constant flux on the left

Spreading in the direction of the mean flow is due to the combined effect of the variation of velocities inside the pores (the tracer follows the streamlines) and molecular diffusion between streamlines that smears the color near the entrance (Figure 1). The molecular diffusion allows the invasion of the tracer in “dead-end” pores and zones with very low velocities.

We can derive the dispersion equations (relationships between flux and concentration) in some limiting cases:

**Piston-type flow:** A theoretical case of transport without any dispersion (not possible in porous media). All the particles are transported at the same Darcy velocity  $U$ . The flux density is therefore:  $f = UC$ .

**Pure molecular diffusion:** With no velocity, spreading is due to molecular diffusion and Fick’s law gives the flux density proportional to the concentration gradient. In a liquid, the coefficient of proportionality is the molecular diffusion  $D_m$ . In a porous media, this coefficient is an apparent diffusion coefficient  $D_A$ . Its ratio with  $D_m$  reflects the presence of solid and pore space tortuosity:  $D_A/D_m = 1/f_f$  where  $f_f$  is formation factor:  $f = -\phi D_A \frac{\partial c}{\partial x}$ .

**Hydrodynamic dispersion:** With no molecular diffusion, the spreading due to pore scale variations in the velocity field can be described using a stochastic approach. If the distribution of pore size is random with no spatial correlation, the invasion of the tracer follows the statistic law of large numbers of uncorrelated events, and the spreading is proportional to the square root of distance (similar to the macrodispersion described below). This mechanism can be represented by a transport equation, sum of a convective term (plug flow without spreading) and a diffusive term leading to the spreading in square root of travelled distance with a dispersion term  $D_c$ :

$$f = UC - \phi D_c \frac{\partial c}{\partial x}. \quad (2)$$

When both molecular diffusion and pore scale velocity field act together, the mechanism is called “microdispersion” and the flux density is assumed to have the same form as Eq.

2 but with a dispersion coefficient  $D$  that includes molecular diffusion and hydrodynamic dispersion.

### Effect of molecular diffusion on microdispersion

Microdispersion involves both molecular diffusion and hydrodynamic dispersion (Pfannkuch in 1963 [1]; Fried and Combarous [2]). The balance between molecular diffusion and hydrodynamic dispersion is quantified using the molecular Péclet number, defined as the ratio of the molecular diffusion characteristic time  $l^2/D_m$  to the advective characteristic time  $l/v$ :  $Pe_m = vl/D_m$ , where  $v$  is a characteristic velocity (i.e. Darcy velocity  $U$  or front velocity  $V = U/\phi$ ).  $l$  is a characteristic length, i.e. mean grain diameter for unconsolidated porous media or of the order of  $\sqrt{K}$  for a consolidated media. Pfannkuch presented a graph with dispersion coefficient normalized by molecular diffusion as function of Péclet number (Figure 2).

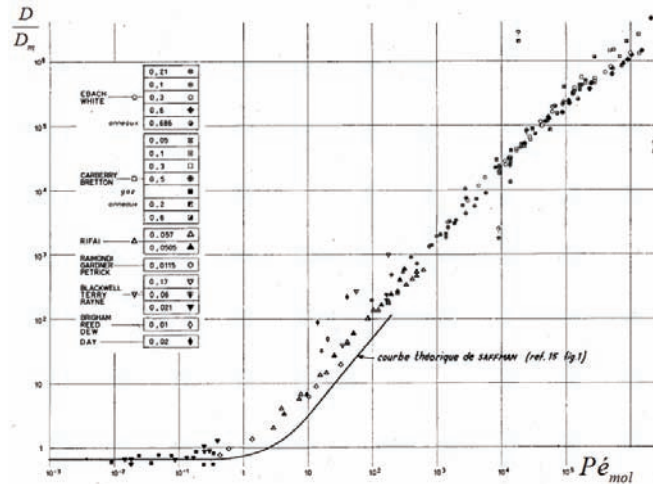


Figure 2 – Dispersion coefficient as function of Péclet number (after Pfannkuch [1]).

At very low flow rate ( $Pe < 1$ ) The dimensionless dispersion coefficient is constant and equal to the apparent molecular diffusion coefficient, a regime of pure diffusion controlled by the apparent diffusion coefficient  $D_A$  described above. For  $Pe > 1000$ : the dispersion coefficient is roughly proportional to the Péclet number. In this regime the dispersion coefficient is independent of molecular diffusion and proportional to the front velocity:

$$D = \alpha V \quad (3)$$

$\alpha$  is called the dispersivity and is around 1.8 times grain diameter for granular material.  $V$  is the front velocity  $V = U/\phi$ , with  $U$  the Darcy velocity. In laboratory, the determination of the dispersion coefficient is performed in this regime.

### DISPERSION THROUGH A PLUG

In laboratory, the dispersion coefficient is derived from tracer injection through a cylindrical plug with uniform injection and production on the inlet and outlet faces. The concentration is measured in the effluent and sometimes locally using in-situ

measurements (X-rays, resistivity, etc.). A constant concentration  $C_0$  starting at time  $t=0$  is injected continuously. Several models have been proposed for the boundary conditions:

### Inlet boundary condition

In laboratory, even if the tracer is injected at constant concentration, it is the flux that is imposed at the entrance and not the concentration. This is well illustrated in a micromodel (Figure 1): A tracer is injected at a constant concentration on the left-hand side of the picture. Considering this picture as a REV, the concentration is constant at the pore scale, in the first rows of pores, but not at the REV scale. Consequently, the boundary condition at the REV scale should be a constant flux density  $f = QAC_0$ . However, experimental data are often interpreted with a constant concentration boundary condition. We will compare these two assumptions when presenting the experimental results, but the difference is insignificant.

### Outlet boundary conditions

In pure molecular diffusion (without flow), the outlet boundary condition should be the concentration imposed at the outlet face. In hydrodynamic regime, the tracer follows the streamlines from inlet to outlet with no backflow. Velocity and dispersion inside the plug are not influenced by the value of concentration at the outlet or the length of the plug. The equation is the same as for an infinite medium, with the condition of zero flux at infinite distance (non infinite mass).

### Dispersion through a homogeneous plug

In a homogeneous plug, permeability is uniform and flow lines are parallel to the axe of the plug. The velocity is uniform and a 1-D mass balance equation can be written (equation 1). Using the microdispersion relationship between flux and concentration leads to the standard 1-D dispersion equation.

$$\partial C / \partial t + U / \phi \partial C / \partial x = \phi D (\partial^2 C) / \partial x^2 \quad (4)$$

Analytical solutions are obtained using Laplace's transforms. With the "classical" assumption of constant concentration at entrance, the solution is the following (Fried & Combarous [2]):

$$C = \frac{C_0}{2} \operatorname{erfc} \left( \frac{x-Vt}{2(Dt)^{1/2}} \right) + \frac{C_0}{2} \exp \left( \frac{Vx}{D} \right) \operatorname{erfc} \left( \frac{x+Vt}{2(Dt)^{1/2}} \right) \quad (5)$$

With the condition of constant flux at the entrance, the solution is:

$$f = \frac{f_0}{2} \operatorname{erfc} \left( \frac{x-Vt}{2(Dt)^{1/2}} \right) + \frac{f_0}{2} \exp \left( \frac{Vx}{D} \right) \operatorname{erfc} \left( \frac{x+Vt}{2(Dt)^{1/2}} \right) \quad (6)$$

Then the concentration is calculated using the mass balance equation with the boundary condition:

$$C = \frac{C_0}{2} \left( \operatorname{erfc}(z_1) - \left( 1 + \frac{V}{D}(x + Vt) \right) \exp \left( \frac{Vx}{D} \right) \operatorname{erfc}(z_2) + \left( \frac{V^2 t}{\pi D} \right)^{1/2} \exp(-z_1^2) \right), \quad (7)$$



$$\text{with } z_1 = \frac{x-Vt}{2(Dt)^{1/2}} \text{ and } z_2 = \frac{x+Vt}{2(Dt)^{1/2}}$$

At the outlet face, the flux density is derived from the measurement of the effluent concentration  $C$ . The calculation is similar to the inlet flux:  $f(L, t) = QC/A$ . The concentration of the effluent is not equal to the concentration at the outlet inside the plug (difference between flux and concentration), such as immiscible flow where fractional flow (flux) is not equal to saturation.

### Dispersion through a heterogeneous plug

In heterogeneous media, the permeability is non-uniform and spreading is mainly controlled by the variation of velocity due to permeability heterogeneity. This type of dispersion is called macrodispersion because mechanisms are at a higher scale than the pore scale. Except in artificial media such as filters or chromatographic columns, spreading due to microdispersion is generally negligible compared to macrodispersion.

#### The 2 or 3 -D approach

Figure 3(a) shows two examples of heterogeneous permeability fields with the calculation of flow lines (b) solving Darcy's equation for an incompressible fluid and the simulation of injection of a tracer in black (c) [3]. The tracer is displaced along the flow lines and is transported according to the local velocities. In these simulations, microdispersion is assumed to be negligible and the tracer is a piston-type displacement along the flow line (either black and white, no grey).

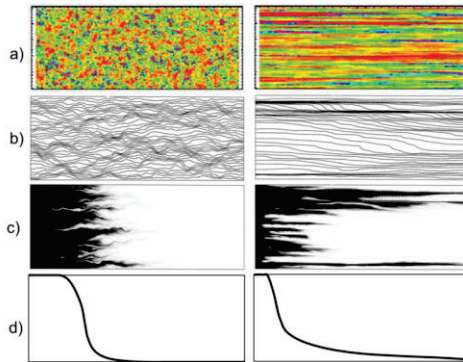


Figure 3- Two examples of heterogeneous permeability fields with the corresponding flow lines and tracer injection assuming piston-type displacement along the flow lines.

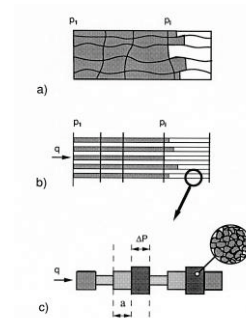


Figure 4 – Principle of stochastic calculation for spreading in a heterogeneous plug

#### Homogenization for 1-D flow

Macrodispersion can be described by hydrodynamic dispersion model (Eq. 2) that accounts for 2 or 3 -D local heterogeneities. However, in laboratory studies, plugs are rarely described using 2 or 3 -D permeability fields. Instead 1-D models with variables averaged over a cross-section are used, and the 1-D permeability becomes uniform, this is called “homogenization”. (Figure 3 d). With the “local” plug-flow rule  $f = UC$  in a 1-D

model, there will be no spreading. The information on heterogeneity is lost, and the local dispersion equation must be changed. We study below three cases of homogenization: random, stratified, and intermediate medium.

Random permeability field in the flow direction

Gelhar and Axness [4] assumed a diffusive process with proportionality between the flux and the concentration gradient (as in Fick's law) with a lognormal permeability distribution. They derived an expression for the dispersion coefficient  $D = V\alpha$ , where the dispersivity  $\alpha$  is related to the variance of the logarithm of permeability  $K$  and the correlation length  $\lambda$ :  $\alpha \propto \lambda \sigma_{LogK}^2$ . However, mechanism at the origin of dispersion is not the concentration gradient but the spatial variations of the velocity field.

A model only based on hydrodynamic spreading can leave to the same result The principle is represented in Figure 4 [5]: the complex stream tubes geometry (a) is modeled by a bundle of parallel tubes (b) with variable cross-section area of elementary volumes (c). The tracer front is irregular due to randomness in the elements volumes. The spreading of the front is calculated as a function volumes linked to the permeability distribution. The result is similar to Gelhar if randomness is assumed (correlation length small compared to travelled distance) and transport equation is similar to the microdispersion case equation (4), but with a dispersion coefficient linked to the size of heterogeneity (correlation length) instead of pore size. The spreading is "diffusive" and the width of the front grows with the square root of travelled distance. This model will be noted "D" for the simulations, with the two possibilities for the inlet boundary condition: constant flux or constant concentration. The corresponding flux and concentrations are given by Eq. 5 to 7.

Homogenization: stratified medium

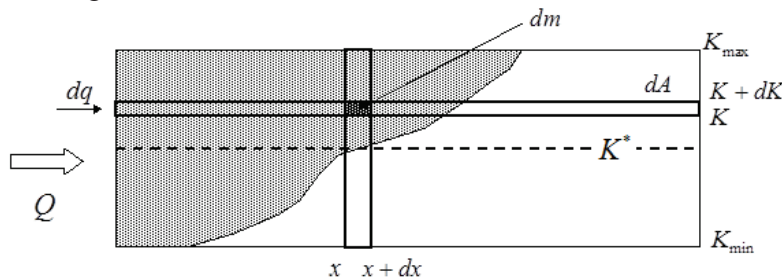


Figure 5 - Perfectly layered medium: principle of the calculation of a tracer transport

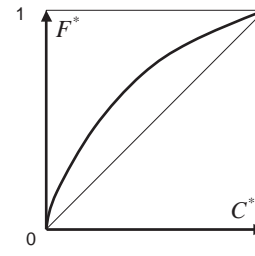


Figure 6 - relationship between flux and concentration for a stratified medium

Stratified media have been extensively used as model of heterogeneous media either for immiscible or miscible flows (for instance Fourar [6], and with a simplified model of 2 layers by Dauba et al. for carbonate studies [7]).

The heterogeneous porous medium is represented by a perfectly layered medium with a permeability distribution function  $G(K)$ . Microscopic dispersion is assumed to be negligible and the tracer follows the streamlines. To simplify the calculation, the layers

are re-arranged with increasing permeability (Figure 5). At a given time, the front of tracer is calculated using the flow rate in each layer and the concentration, by averaging over the cross-section:

$$C(x, t) = C_0 \int_{K^*}^{K_{max}} G(K) dK, \quad (8)$$

where  $K^* = \frac{K_{eq} x}{v t}$  is the lower limit of the invaded layers and  $K_{eq}$  is the effective permeability. The flux at the same position is calculated by summing the flow rates in all invaded layers:

$$F(x, t) = \int_{K^*}^{K_{max}} C_0 dq = C_0 Q \frac{1}{K_{eq}} \int_{K^*}^{K_{max}} K G(K) dK. \quad (9)$$

In the general case, there is no analytical relationship between flux and concentration, but the curve can be determined numerically by elimination of the parameter  $K^*$ . The shape is similar to the fractional flux curve for immiscible flow, but without the front discontinuity (Figure 6). The transport equation is “convective” with no second order derivative and the width of the front is proportional to travelled distance.

Fourar [6] used a lognormal permeability distribution and defined a heterogeneity factor as the ratio of the standard deviation to the effective permeability. Here we will keep the general form of the permeability distribution.

#### Homogenization: general case

For real rock samples, the spreading is a combination of “convective” flow in the channels of various permeabilities (preferential paths) and “diffusive” spreading inside these channels due to random heterogeneities.

One approach is to use the stochastic tube model with long-range correlations to represent the transition between diffusive and layered. Results are close to the Continuous Time Random Walk model introduced by Berkowitz [8]. Models with non-integer derivative order (between 1 for convective and 2 for diffusive) have also been proposed [9].

In this study, we tested a simpler empirical model called H-D [10], built as the sum of a convective term and a diffusive term:

$$f = \frac{f_H}{c} \left( U C - D \frac{\partial C}{\partial x} \right), \quad \text{with } f_H = \frac{c}{c+(1-c)/H}. \quad (10)$$

This approach is justified by assuming that convective effects take place at a larger scale than dispersive effects. The calculation is similar to the microdispersion case, but instead of the front velocity in the flux equation, an apparent front velocity is used since the injected fluid is moving faster.

## **EXPERIMENTAL RESULTS**

Tracer are injected at constant concentration, using 35 and 20 g/l NaCl solutions. Several plugs have been leading to similar results. Experiment 8 described here is performed on a 5 cm long Claschasch sandstone plug, 1 inch in diameter, with porosity 0.14 and permeability 300 mD. In-situ concentration profiles are measured along the plug with 10 electrodes. The effluent concentration is measured with a conductimeter placed 5 cm from



the outlet face. Injection is performed through a spiral groove, flushed before the beginning of the experiment. Injection rate is 10 cc/h with a Pharmacia pump. Temperature is controlled at 0.2 °C accuracy (ion conductivity is strongly dependent on temperature).

### Effluents

The measured effluent flux normalized between 0 and 1 is plotted in Figure 7 as function of dimensionless time (unity corresponds to the time needed to displace the pore volume).

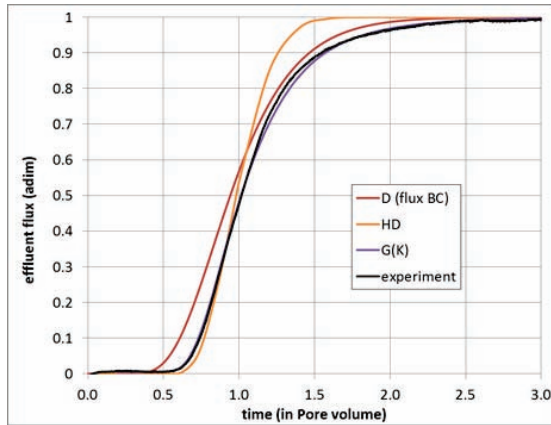


Figure 7 - Effluent flux profiles: experiment and models.

For the stratified model, the permeability distribution “from effluent” is derived by plotting the experimental flux (figure 7) as a function of  $x/t$  and calculating  $G(K)$  after fitting by spline functions, following Eq. 9. The  $G(K)$  “from concentration” is calculated from the measured concentration using Eq. 8. The results are plotted in Figure 8 in dimensionless form. Curves noted D, HD,  $G(K)$  are best fits with the corresponding models (models defined below).

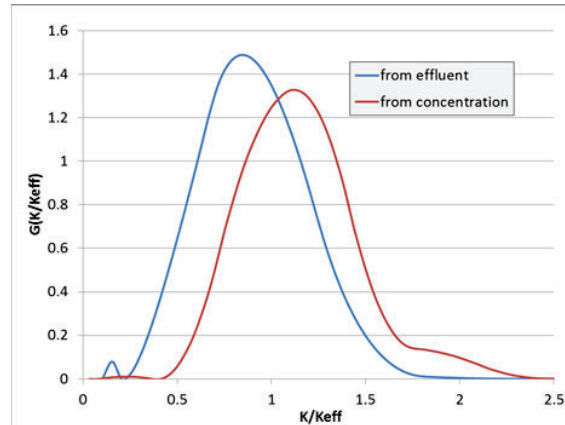


Figure 8 – Permeability distribution  $G(K)$  calculated from effluent flux and in-situ concentrations.

### Concentration profiles

Only 5 profiles over the 10 measured are represented in Figure 9 for better readability of the figures. Symbols represent experiments and the solid lines are the results of the 4 models using CYDAR™:

- D model with the two boundary conditions at entrance: constant concentration (conc. BC, Eq. 5) or constant flux (flux BC, Eq. 7)
- HD model with convective and dispersive terms (Eq. 10), manually adjusted for the best fit.
- Stratified model with  $G(K)$  calculated using Eq. 10. In this equation, the variable is  $K^*$  proportional to  $x/t$ . Therefore, all concentration profiles are plotted as function of the scaling variable  $x/t$  and data are fitted using splines functions (Figure 10). The permeability distribution  $G(K)$  derived from concentration profiles is plotted in Figure 8 for comparison to the value derived from the effluent flux.

In Figure 10, we have also plotted the concentration profiles for the model D with the scaling variable  $(x - Vt)/\sqrt{t}$ . If the experiment follows the model D, all points should collapse on the same curve.

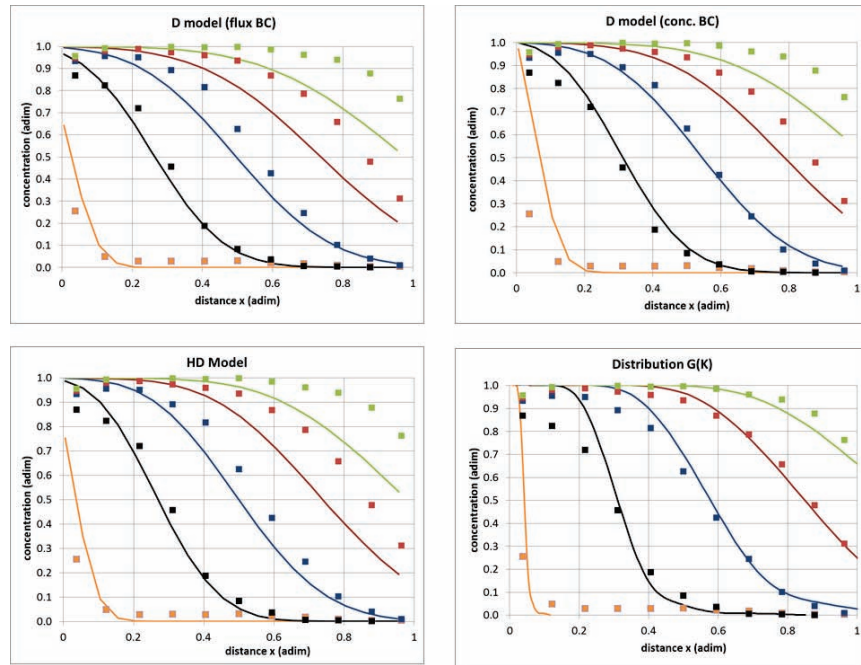


Figure 9 – In situ concentration profiles measured along the plug at different times. Symbols represent the experiment and the solid lines are the results of the various models at the same times. For the flux and concentration D model,  $D=0.05$  (dimensionless). For the HD model,  $D=0.025$  and  $H=1.1$ .

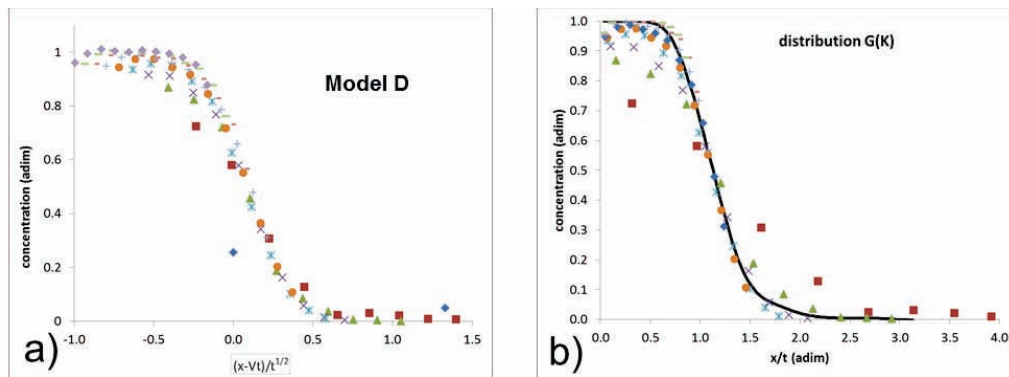


Figure 10 – a) Scaling laws for the measured in-situ concentration profiles for the D model (scaling in  $x - Vt/\sqrt{t}$ ) - b) the stratified G(K) model (scaling in  $x/t$ ).

## DISCUSSION

### Effluent profiles

Models D and HD cannot reproduce the dissymmetry and the long tail of the effluent flux production accurately (Figure 7). 2-D numerical simulations performed on heterogeneous

permeability field with intermediate correlation lengths permeability field show that the injected fluid starts to flow in permeable zones of the medium (channeling), leading to a fast displacement. At the end of the displacement, the injected fluid flows in much lower permeability zones and the production is slower, explaining the dissymmetry of the curve. Recently Zik et al. [11] used a model involving exchange by molecular diffusion between flowing and stagnant zones (model generally called Coats and Smith). This model allows the representation of long tails by diffusion, but the representation of the concentration profiles have not been experimentally verified. From the estimate of the diffusion time scale, this effect might be valid in chromatographic columns, but comes into play at a different scale for displacement in heterogeneous plugs. The agreement between experiments and results of  $G(K)$  model is good since this distribution is calculated from the effluent. The small differences are introduced by the fit with splines functions.

### Concentration profiles

1) From Figure 9, we see that the best fit is obtained with the stratified model, using the  $G(K)$  permeability distribution. However, the first profiles are not well represented; the model gives the maximum concentration in contradiction with the experiment. This discrepancy is also visible in Figure 10, where the brown squares represent the first profile. This discrepancy could be an experimental artifact during flushing of the inlet end-piece spiral, with displacing fluid entering partially into the plug.

2) D model with the flux boundary condition is the only model that represents the increase of concentration at the entrance. However, after a small distance, both boundary conditions give similar results.

3) Scaling laws for the D and  $G(K)$  models (Figure 10) lead to similar results. Therefore this test cannot efficiently discriminate between models.

4) The  $G(K)$  distributions determined from the flux and the one determined from the concentration (Figure 8) are different, although  $G(K)$  should theoretically be unique. The observed difference may arise from a delay in effluent production in the outlet spiral. The volume of the outlet spiral is not negligible (0.3 cc compared to 5 cc of pore volume). This dead-volume introduces a delay that would lead to a lower observed permeability.

## CONCLUSION

When used as local input in 3-D simulations, the Darcy-scale approach can accurately describe the plug-scale spreading related to permeability heterogeneity. In a 3-D heterogeneous medium, even a displacement started as piston-type at the Darcy-scale leads to a dispersion behavior due to the spatial differences in velocities.

- We have presented several up-scaled (or homogenized) models: microdispersion, macrodispersion, convective channeling).
- Our results confirm previously published results that channeling convective models are more suitable than the standard dispersion models.
- The best result is obtained by calculating a permeability distribution function  $G(K)$  in a stratified model. This model captures both the long tail in the effluent production and the in-situ concentration profiles.

## REFERENCES

- [1] H.-O. Pfannkuch, «Contribution à l'étude des déplacements de fluides miscibles dans un milieu poreux», Revue de l'Institut Français du Pétrole et annales des combustibles liquides, vol. 28, pp. 1-54, 1963.
- [2] J. J. a. C. M. A. Fried, «Dispersion in Porous Media», Advances in Hydroscience, vol. 7, pp. 169-282, 1971.
- [3] R. Lenormand and M. Thiele, «Homogeneization of Flow equations with viscous Instabilities: Numerical Validation of the MHD model», European Conference on the Mathematics of Oil recovery (ECMOR V), 1996.
- [4] L. W. Gelhar and C. L. Axness, «Three-dimensional stochastic analysis of macrodispersion in aquifers», Wat. Resour. Res., vol. 19, pp. 161-180, 1983.
- [5] R. Lenormand, «A stream tube model for miscible flow. Part 1: Macrodispersion in homogeneous porous media», IEA Collaborative Project on Enhanced oil Recovery, Salzburg, Austria, 1993.
- [6] M. Fourar, «Characterization of heterogeneities at the core-scale using the equivalent stratified porous medium approach», SCA2006-49, Trondheim, Norway, 2006.
- [7] C. Dauba, G. Hamon, M. Quintard and F. and Cherblanc, «Identification of parallel heterogeneities with miscible displacements» SCA paper 9933,, Golden, USA, 1999.
- [8] B. a. S. H. Berkowitz, «The role of probabilistic approaches to transport theory in heterogeneous media», Transport in Porous Media, vol. 42, pp. 241-263, 2001.
- [9] R. Lenormand, «Use of Fractional Derivatives for Fluid Flow in Heterogeneous Media», 3rd European Conference on the Mathematics of Oil Recovery, 1992.
- [10] R. Lenormand, «Determining Flow Equations from Stochastic Properties of a Permeability Field», SPE Journal, vol. 1, 1996.
- [11] B. Vik, K. Djurhuus, D. Doublet, K. Spildo and A. Skauge, «Characterization of vuggy carbonates by miscible process», SCA2008-28, Abu Dhabi UAE, 2008.
- [12] F. A. L. Dullien, «Porous Media: Fluid Transport and Pore Structure», Academic Press ed., San Diego, California, 1992, p. 574.
- [13] K. Sorbie, H. Zhang and N. Tsibuklis, «Linear viscous fingering: new experimental results, direct simulation and the evaluation of averaged models», Chemical engineering science, vol. 50, n° %14, pp. 601-616, 1995.
- [14] A. Koval, «A Method for Predicting the Performance of Unstable Miscible Displacement in Heterogeneous Media», SPE Journal, pp. 145-154, June 1963.
- [15] M. Sahimi, M. R. Rasaei and M. Haghghi, «Gas injection and fingering in porous media», Gas Transport in Porous Media, C. Ho and S. Webb, Eds., Springer, 2006, pp. 133-168.
- [16] M. Fourar, G. Konan, C. Fichen, E. Rosenberg, P. Egermann and R. Lenormand, «Tracer tests for various carbonate cores using X-Ray CT», SCA 2005-56, Society of Core Analysts, Toronto, Canada, 2005.
- [17] A. Fick, «Ueber Diffusion», Annalen der Physik, vol. 170, pp. 59-86, 1855.
- [18] K. H. Coats and B. D. Smith, «Dead-end pore volume and dispersion in porous media», Society of Petroleum Journal, pp. 73-84, 1964.
- [19] G. Taylor, «Dispersion of soluble matter in solvent flowing slowly through a tube», Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences, vol. 219, pp. 186-203, August 1953.
- [20] G. Taylor, «The Dispersion of Matter in Turbulent Flow through a Pipe», Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, The Royal Society, vol. 223, pp. 446-468, 1954.
- [21] R. Aris, «On the Dispersion of a Solute in a Fluid Flowing through a Tube», Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, The Royal Society, vol. 235, pp. 67-77, 1956.