"ORIGIN OF SCALE-DEPENDENT DISPERSIVITY AND ITS IMPLICATIONS FOR MISCIBLE GAS FLOODING"

SEMI-ANNUAL REPORT

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Origin of Scale-Dependent and Its Implications for Miscible Gas Flooding

Dr. Steven L. Bryant, PI

Period: April 1, 2006 – September 30, 2006

EXECUTIVE SUMMARY

Over thirty years of field experience in using carbon dioxide in oil reservoirs shows that ultimate oil recovery efficiencies are small, typically 10% to 20%. The amount of carbon dioxide injected to recover a barrel of oil is large. The maintenance of minimum miscible enrichment and minimum miscibility pressure is an important design consideration that strongly affects efficiency and carbon dioxide utilization. In turn, hydrodynamic dispersion is a key mechanism that influences these operational factors. Dispersivity is known to be scale dependent, but a satisfactory method has yet to be developed that accounts for dispersivity in the simulations on which laboratory interpretation and field design rely. By establishing a better fundamental basis for modeling displacements at multiple scales, this project will provide better tools for industry to improve the effectiveness of gas flooding projects.

The objectives of this project are to perform a novel fundamental study of the mechanism of dispersion, to develop an improved multiscale statistical model of dispersion, and to use this advance in understanding to optimize field scale displacements. A numerical experiment using particle tracking in large scale domains demonstrates that the large echo dispersion coefficients estimated in Mahadevan et al.(2003) are not unreasonable. It could be that irreversible mixing is occurring even in large-scale miscible displacements. For this case, the traditional definition of dispersivity does not apply because the dispersion coefficient does not scale linearly with velocity because of the unidirectional nature of the velocity field. With the use of a heterogeneous velocity field, a linear scaling is expected as demonstrated in particle tracking done on pore-network models(Bruderer and Bernabe 2001).

Our grain-scale simulation studies show that the echo test in parallel layers is scale-dependent when there is transverse flow between layers. We also show that transverse dispersion is significant when velocity fluctuation in the transverse direction is high and that the transverse dispersion value depends on the medium configuration. In this study we calculated transversal and longitudinal dispersion in a 2D homogeneous configuration by applying an inverse fit method to match the simulation concentration data to the 2D analytical solution of the convection-dispersion equation. We show that, in the case of zero diffusion in pore-scale simulations, local mixing would be reversible when flow is at low Reynolds number.

The progress to date is meeting the expectations laid out in the project description.

GOAL

The objectives of this project are to perform a novel fundamental study of the mechanism of dispersion, to develop an improved multiscale statistical model of dispersion, and to use this advance in understanding to optimize field-scale displacements.

PERFORMERS

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RESULTS OF WORK DURING REPORTING PERIOD

Modeling tracer dispersion in layered flow using particle tracking

We have used the concept of flow reversal (Jha, John et al. 2006) to test if the dispersivities obtained at the field scale represent mixing or if they are an artifact of averaging and represent conformance. True mixing is irreversible upon change in flow direction. We simulated tracer dispersion is two-dimensional layered flow and computed the evolution of the longitudinal dispersion coefficient (averaged over the vertical cross section) in both forward and reverse flow.

The flow domain consists of five layers of equal thickness and different velocities as in Figure 1. The height of the medium is 1 m and the evolution of spatial variance of the particles (from which the dispersion coefficient is derived) is computed with increasing time (equivalent to mean distance traveled) and velocity for both forward flow and reversed flow schemes. For all cases, we begin with an ensemble (a swarm) of 2000 particles at x = 0 and move them to the right (forward flow) or left (backward flow) as required by the case being investigated.

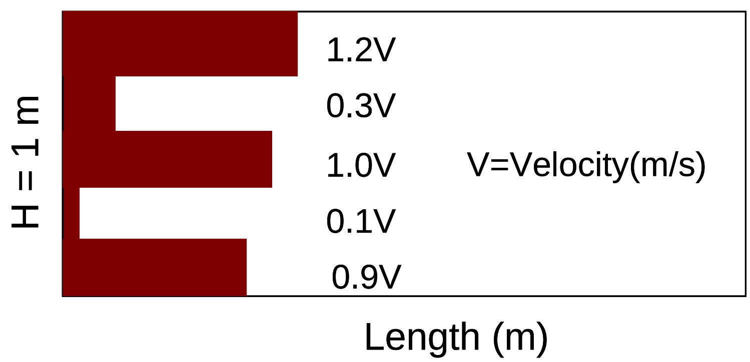

Figure 1. Model for layered flow. The velocity distribution is fixed and can be rescaled by changing V. Transport is simulated using particle tracking based on convective and diffusive steps. Transverse movements are because of diffusion only.

For the case with no diffusion, the distribution of particle positions (the concentration profile) at two different times is shown in Figure 2 (top). On flow reversal, the tracer particles retrace their trajectory (on the same streamline) and there is no local mixing as shown in Figure 2 (bottom).

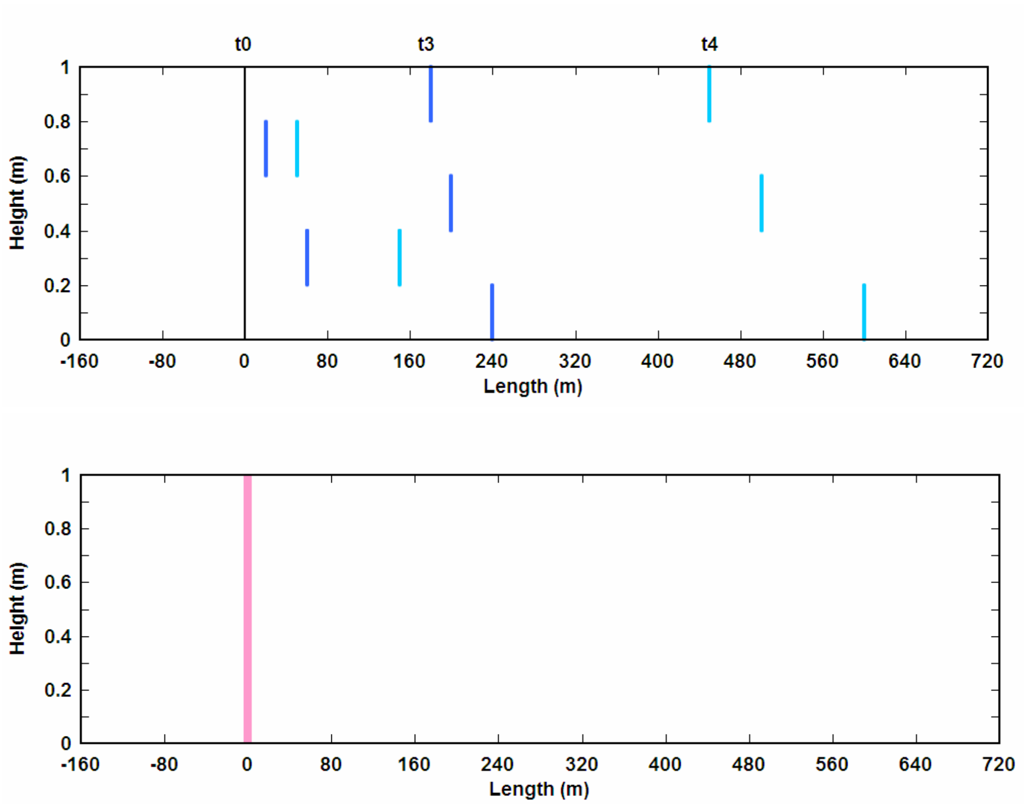

Figure 2. Transport with no diffusion. Particle locations plotted at two different times in forward flow (top) and at flow reversal (bottom). The system never reaches transverse equilibrium. Echo dispersion is zero.

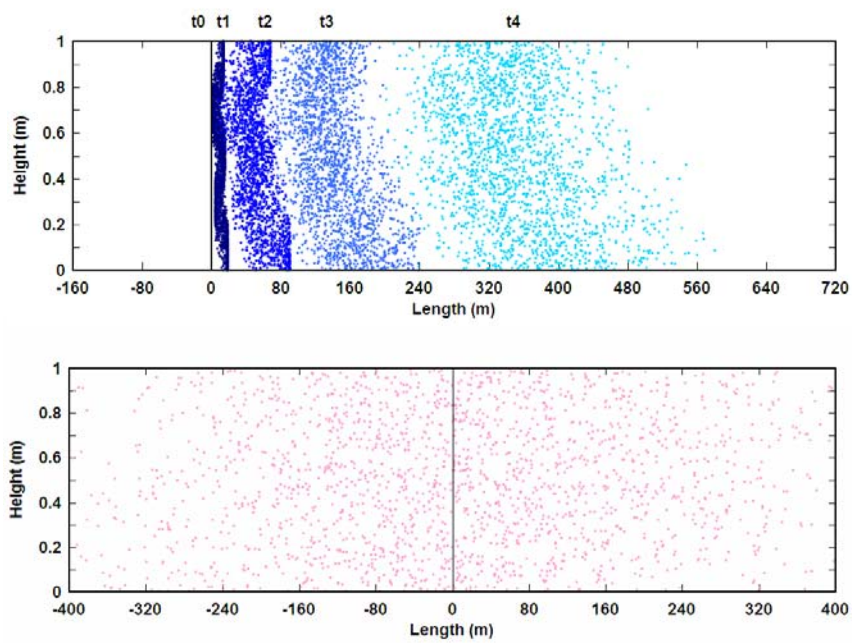

Figure 3. Transport with diffusion (D=1E-9 m^2/s). Particle locations plotted at four different times showing evolution of spatial variance (top) and at flow reversal (bottom). System is tending to transverse equilibrium under the action of diffusion alone. Echo dispersion is non-zero.

For the same flow but with diffusion, the profiles are in Figure 3. Note that, even though the spreading in the transverse direction is because of diffusion alone, the concentration (number of particles/area) is beginning to homogenize in the transverse direction after traveling about 400m to the right. On flow reversal, the particles no longer retrace the same outgoing path as they return to the inlet. The diffusive jumps cause them to sample different streamlines on the return path. The large spread of the particles about the inlet indicates large mixing in both transverse and longitudinal directions.

Figure 4 shows the evolution of the dimensionless dispersion coefficient (dispersion coefficient divided by diffusion coefficient) with mean distance traveled. The dimensionless dispersion coefficient increases to an asymptotic value of about 5000 (that is 5000 times larger diffusion) at about 2000m.

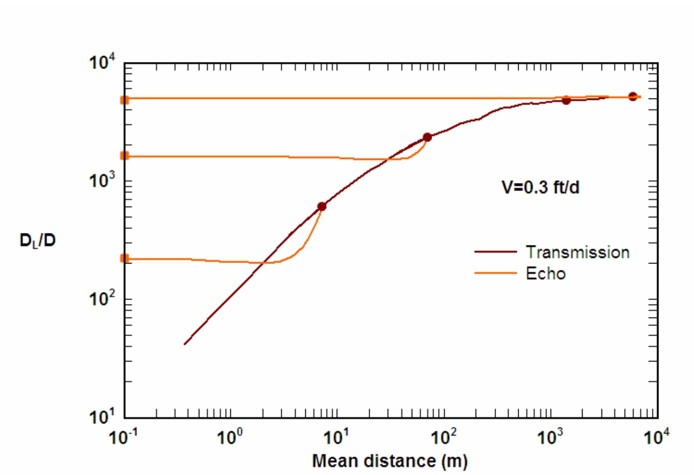

Figure 4. Evolution of dispersion coefficient with mean distance travelled in forward and reverse directions. Disperison coefficient slowly increases and reaches an asymptotic limit. Echo values increase with penetration distance. Diffusion coefficient is 1E-9 m^2/s.

After flow is reversed from four different distances, the evolution of the echo dispersion coefficient is computed for the swarm as it returns towards the inlet. As they return, the echo dispersion coefficients decrease at first and then stabilize when the swarm nears the original inlet. The larger the travel distance, the smaller is the decrease to the point that when transmission dispersion stabilizes, the echo dispersion does not decrease at all. The echo dispersion coefficients progressively increase with the penetration distance finally reaching the same value as the asymptotic transmission value. The echo dispersion at this distance evidently has no convective component. This very large value (5000) indicates that local mixing could be very large.

At smaller distances, the forward spreading is still convection dominated (the transmission dispersion coefficient is still increasing). Since the echo dispersion at short distances abruptly decreases immediately on flow reversal there must be a substantial convective component to the transport. The same simulation was repeated for lower velocities as summarized in Figure 5 where the results are compared over four length scales. Smaller velocities are equivalent to increasing the molecular diffusion coefficient as would be expected in gas-gas binary flow. The same trend in dispersion coefficient growth occurs but the asymptotic value is reached much closer to the inlet (up to 200m for the case with slowest velocity). The echo dispersion coefficients compare in the same way, being lower than the transmission values at short distances and equal to it at its asymptotic value. The fact that the echo dispersion coefficients also decrease with decrease in velocity indicates the significance of convection in enhancing local mixing.

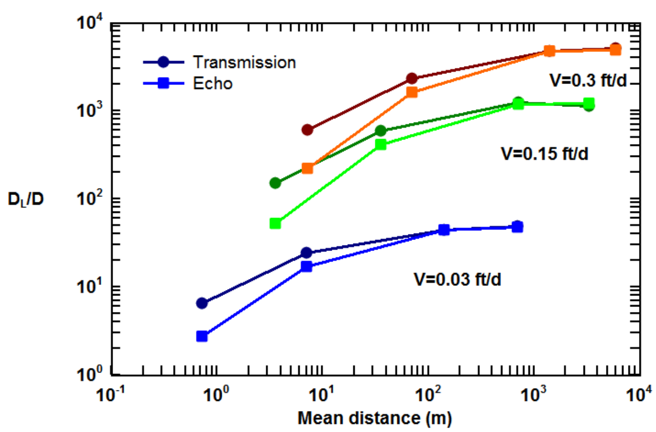

Figure 5. Comparison of forward and echo dispersion coefficients at different velocity ranges. At slower velocities (equivalent to higher diffusion) distance to reach asymptotic limit is less.

Grain-scale simulation results for heterogeneous domains: Parallel layer porous media

We performed echo tests to investigate the impact of layering and transverse flow on scale dependent dispersivity in a heterogeneous porous media. We carried out simulations for the cases of no transverse flow between layers by separating the layers and with transverse flow between layers. Then we reversed flow at various penetration length and measured dispersivity from concentration history at the inlet. Figure 6 shows the measured echo dispersivity in the parallel layers pore-scale simulation with and without transverse flow. It can be seen clearly from the Figure 6 that dispersivity in parallel layer is scale dependent when there is communication between layers.

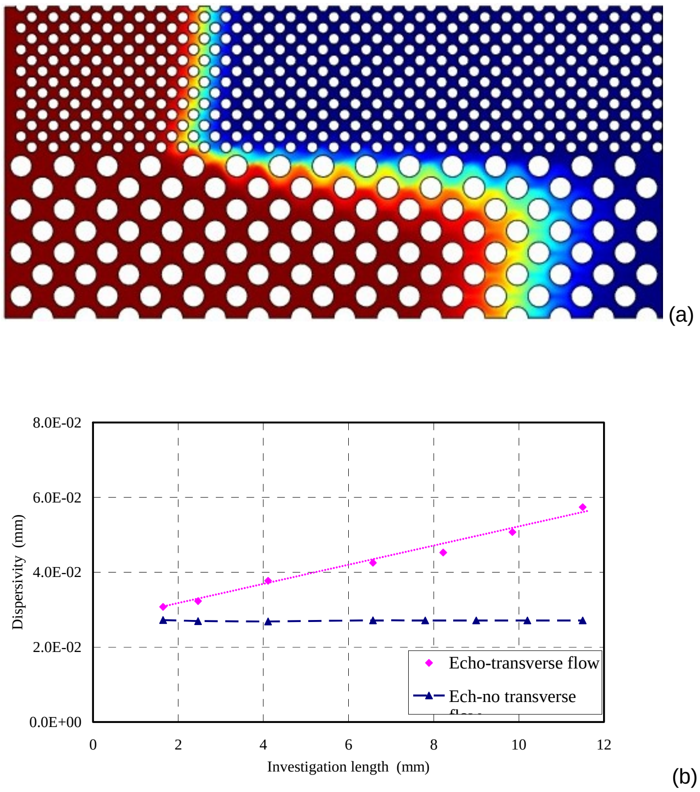

Figure 6. a) Parallel layer configuration in pore-scale simulations b) Comparison of measured dispersivity vs. investigation length of echo test with transverse flow and without

Transverse dispersion

In 2D homogeneous pore-scale simulation, the velocity inside the medium varies widely in both directions since porosity is high, thus transverse dispersion is significant. We have calculated transverse and longitudinal dispersion simultaneously for the 2D homogeneous case (Figure 7) by applying inverse fit method to match solute concentration history of the pore-scale simulation to the 2D analytical solution of the convection-dispersion equation. The transverse dispersion has been calculated for local mixing (pore measurement of concentration history) and overall mixing (average concentration over a cross section). Figure 7 shows the 2D homogeneous porous media and calculated transversal and longitudinal dispersion. Since geometry was symmetric we used half of the porous media configuration for our simulations.

The results show that local transverse mixing decreases as moving forward in the flow direction until it reaches to a constant value. It can be observed that transverse dispersion is much larger than longitudinal dispersion as a result of large space to flow in transverse direction to the bulk flow. So we used lower porosity porous media model as shown in Figure 8. As it can be seen in Figure 8, transverse dispersion is less than longitudinal dispersion by order of magnitude.

Since we use the 2D analytical solution to convection-dispersion equation, which is for point measurement of the solute concentration history thus the transverse dispersion calculation for flow averaged concentration history largely depends on the cross-section width. Transverse dispersion increases as traveled distance from the source increase in transverse direction to flow and decreases as traveled distance from the source increase in direction to flow until it reaches to a constant value.

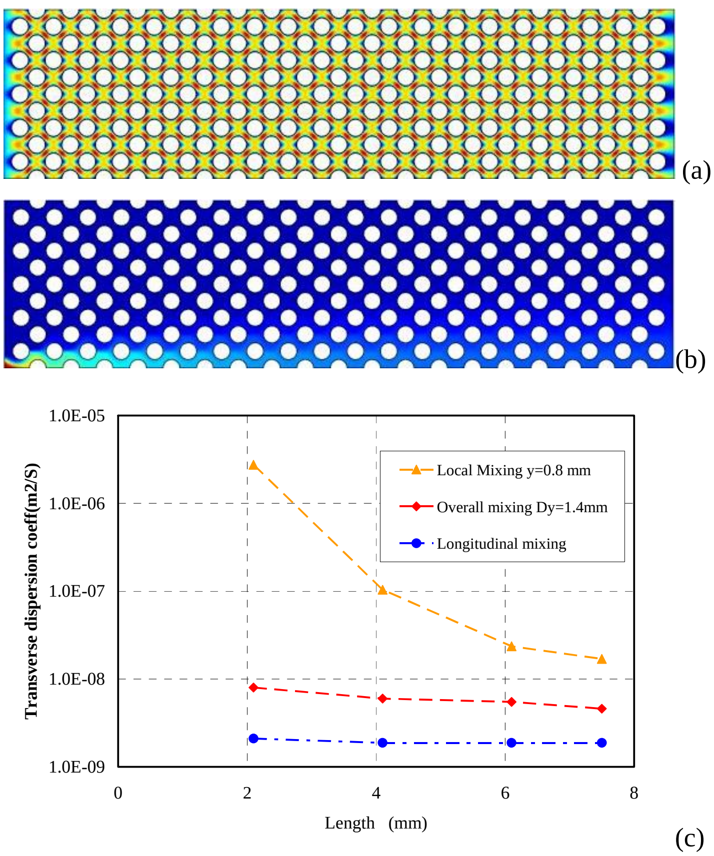

Figure 7. a) Velocity distribution, b) Concentration profile, c) Calculated transverse and longitudinal dispersion for 2D homogeneous porous media

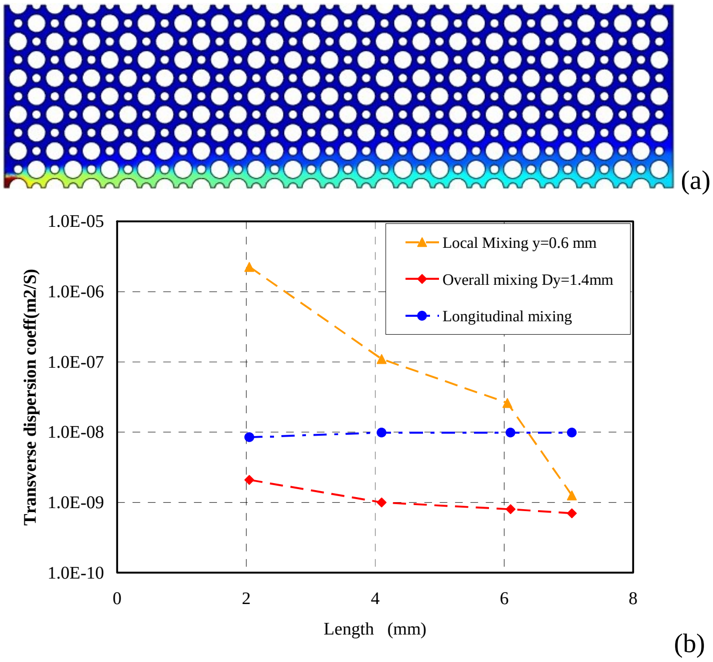

Figure 8. a) Concentration profile, b) Calculated transverse and longitudinal dispersion for lower porosity 2D homogeneous porous media

Reversibility:

It has been well established that the mixing process is an irreversible phenomenon. Molecular diffusion is the primary reason that makes local mixing irreversible. In the case of zero diffusion in pore-scale simulations, local mixing would be reversible when flow is at low Reynolds number. We showed that all streamlines are reversible for low Reynolds number and are irreversible for high Reynolds number. Figure 9 shows that streamlines take the same path in forward and backward flow for low Reynolds numbers. However, for high Reynolds numbers, streamlines take different path in forward and backward flow (Figure 10). All simulations in this study fall in the range of low Reynolds numbers.

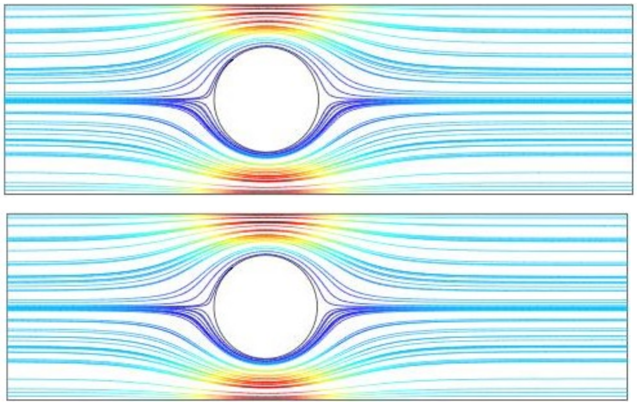

Figure 9. Reversible flow for low Reynolds number Re=0.2, $\mathrm{Re}=\frac{\rho u_o D_p}{\mu}$

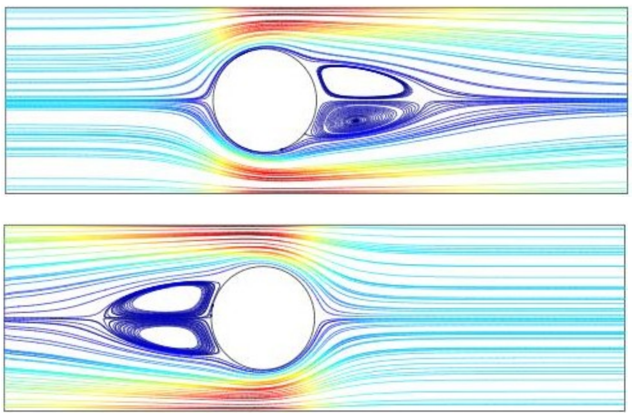

Figure 10. Irreversible flow for high Reynolds number Re=20

Mixing Mechanism and Effect of Flow Reversal on Mixing

We have carried out FEMLAB simulations in two-dimensional porous media consisting of a rectangular plate with circular holes in it. The holes represent the sand grains and the fluid can flow through the pore space between them. The grain diameter is taken as 100 microns. The size of the flow domain is 1800x800 microns. In each case, a solute slug is injected into the medium at a small velocity of 10^{-5} *m/s* for 20 seconds (which corresponds to 0.1 PV, approximately). The outlet face of the medium is maintained at atmospheric pressure. All other boundaries including the sand grain boundaries are of “no-slip” kind. The steady state velocity at each point inside the medium is obtained by solving the Navier-Stokes equation. The solute concentration as a function of time and position is then determined by solving the two-dimensional convection-diffusion equation. This equation uses the computed velocities at each point and an input diffusion coefficient, $D_o = 10^{-11}\ m^2/s$. When the slug reaches the center of the medium the direction of flow is reversed. Solute concentration profiles at a short distance from the inlet can be compared during forward and during backward flow to investigate the degree of irreversibility of mixing.

We test these insights gained from single-pore simulations by conducting flow reversal studies in a disordered arrangement of disks. Even though this model of porous media is two-dimensional and has an unrealistically large porosity, it does capture the basic physics of the process and allows qualitative comparisons with experimental observations.

The velocity inside the medium varies widely both in longitudinal and lateral directions. Therefore, the solute slug does not move uniformly throughout the cross-section of the medium. It spreads more in the regions of high velocity (Figure 11 (a), (b)). The differential movement of different parts of the solute slug across the cross section grows with time and distance traveled. If the slug keeps on moving in the forward direction and effluent concentration is monitored at the outlet, it would not satisfy the 1D convection-diffusion equation (in other words, concentration history curve is non-Gaussian). However, if the flow direction is reversed and effluent concentration history is monitored at the original inlet, the backward or echo dispersion curve becomes Gaussian because the convective spreading gets cancelled upon flow reversal (Figure 12). Cancellation of convective spreading is also evident if we compare solute concentration profiles at the same distance from the inlet in forward and backward flow (Figure 11). The two profiles look similar in shape. However, the backward profile is more dispersed because of irreversible local mixing.

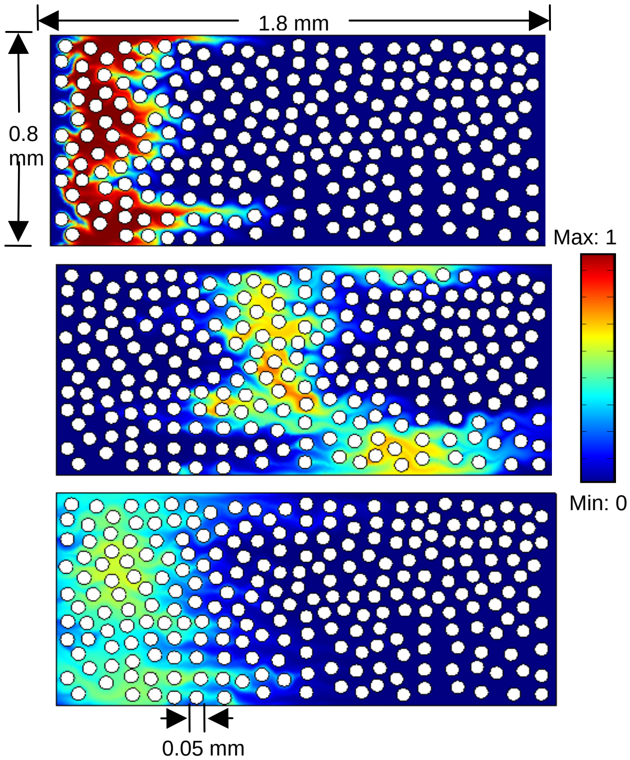

Figure 11. Solute concentration profiles for a slug in irregular arrangement of disks (a) five seconds after injection, (b) at the time of flow reversal and (c) five seconds before exit.

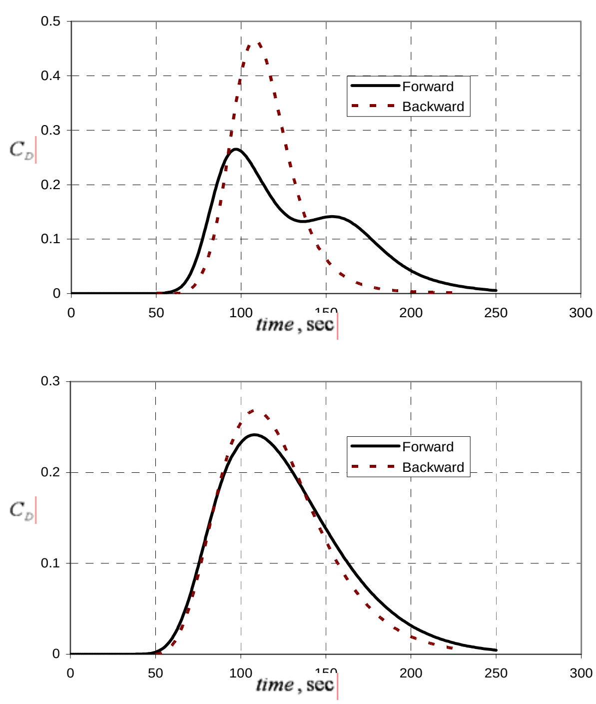

Figure 12. Comparison of solute concentration histories for a slug in irregular packing (a) $Do = 10^{-11}\ m^2/s$ (b) $Do = 10^{-9}\ m^2/s$

Flow Reversibility Simulations in an Ordered Pack

Flow reversal simulations were also carried out for a regular arrangement of disks. In this case the local velocity does not vary widely from point to point and even small diffusion is able to eliminate radial concentration discontinuities in a pore. The solute slug appears to move like a plug. The effect of convection, splitting and rejoining around sand grains is to enhance the effective diffusion coefficient and mixing during flow is “diffusion-like”. It is analogous to case (i) (plug flow) but with a larger dispersion (effective diffusion) coefficient. Upon flow reversal, the slug behaves exactly same way while flowing backward that it would have done while flowing forward. Therefore flow reversal has no effect on mixing and mixing is completely irreversible (Figure13, 14).

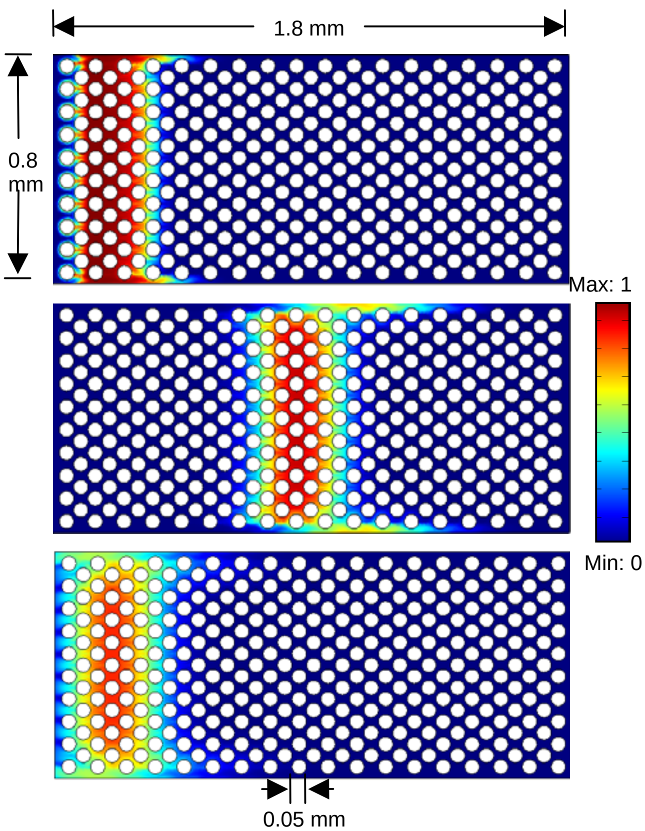

Figure 13. Solute Concentration profiles for a slug in regular arrangement of disks (a) five seconds after injection, (b) at the time of flow reversal, and (c) five seconds before exit. This process is diffusion-like.

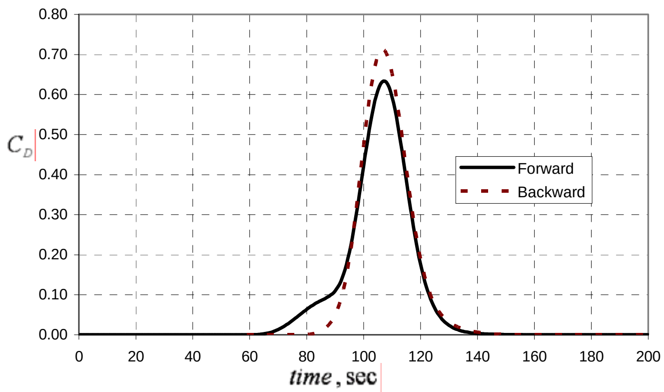

Figure 14. Forward and backward solute concentration histories for flow in a uniform pack (*Do* = 10^{-11} m^2/s). Mixing is irreversible.

BENEFITS

The ultimate oil recovery efficiency from carbon dioxide (CO2) injection is low. The CO2 utilization rate—the amount of CO2 injected to recover a barrel of oil—is high. The performance of a CO2 process is strongly influenced by hydrodynamic dispersion, but the basis for dispersion and rigorous methods for modeling it remain poorly understood. The objectives of this project are to perform a novel fundamental study of the mechanism of dispersion, to develop an improved multi-scale statistical model of dispersion, and to use this advance in understanding how to optimize field-scale displacements.

BACKGROUND

That dispersivity increases with scale (travel distance) has been known for more than 30 years. There is substantial ambiguity about what causes the scale dependence. Part of the work being proposed here is to investigate the scale dependence downward—from the core or column scale to the pore scale—as opposed to upward, as has been done previously. This approach has never been tried as part of an effort to understand the fundamental mechanism of dispersion. The nature of the scale dependence has significant implications for modeling displacements at larger scales, and the project is to incorporate these results with previous model development and with existing numerical simulators. Finally, researchers are to use these improved models and simulators to establish a better grasp of the parameters that control optimal performance in miscible and near-miscible displacements. With this capability, they also will develop better methods for translating results of laboratory tests to field projects.

Mixing in porous media results from a complex interplay of *convective spreading (mechanical mixing)* and *molecular diffusion*. Convective spreading arises due to velocity variations in pore throat and also because of tortuous nature of porous media. On the other hand, diffusion is a result of random motion of molecules when two miscible fluids are in contact.

Traditionally, mixing properties of a porous medium are quantified by carrying out miscible displacement experiments in which one miscible fluid displaces another through a core sample. The flow averaged ("cup-mixed") effluent concentration history is analyzed using a solution to the one-dimensional convection-diffusion equation to quantify core-scale mixing property of the medium, which is usually expressed as the dispersivity.

This process describes *apparent mixing* because it is averaged over the entire outlet and has contributions from convective spreading and diffusive (local) mixing lumped together. It is difficult to ascertain underlying mechanism of mixing inside the medium from cup-mixed concentration histories. We don't know the relative contributions of convective spreading and local mixing how the two interact with each other.

Echo dispersion experiments, in which the direction of flow is reversed after solute has penetrated into the medium (but not exited) to a pre determined distance, help us figure out the nature and mechanism of mixing taking place inside the pore body. Experimental results show (apparent) mixing to be *irreversible* in homogeneous media. The solute continues to mix as the fluid moves back toward the original inlet. Dispersivities obtained from such flow reversal experiments on homogeneous core samples in the lab and from single well tracer tests in field are as large as the corresponding transmission values. On the other hand, echo dispersion experiments on layered media show largely reversible mixing.

A particle tracking code was written to perform calculations using a velocity field given on a three dimensional, cartesian grid. The velocity at each location is computed based on linear interpolation (Goode 1990). The diffusion coefficient is input by the user and this can be set to the value of the molecular diffusion or the lab derived macro dispersion coefficient at the scale of resolution of the velocity field. The particle tracking procedure uses a given velocity field and molecular diffusion to compute the positions of point-like tracer particle released at the origin (Jha, John et al. 2006). The velocity field is assumed to be unidirectional in x and at steady-state. This velocity field is imposed a priori and not computed from a flow simulation in this initial study. For flow reversal, we keep the magnitude of the velocities the same but change the direction from +x to -x instantaneously. This is reasonable for incompressible, slow laminar flow. The net displacement of a particle is the sum of the convective (deterministic) and diffusive (random) displacements.

The longitudinal dispersion coefficient is computed from the spatial variance of the particles at a given time as

$$D_l = \frac{\sigma_x^2}{2t}$$

CONCLUSION

Summary of Significant Accomplishments

The project researchers:

- Used simulated echo tests (push-pull injection) to show that dispersivity is a scale dependent property when transverse flow exists between layers in layered porous media.
- Simulated grain-scale flow to show that transverse dispersion is a scale- and medium-dependent property; transverse dispersion decreases as tracer moves away from the injection source and it ultimately reaches a constant value
- Showed via pore-scale simulations that flow through simple granular materials is irreversible for high Reynolds numbers

- Used the multi-physics modeling software FEMLAB to solve simultaneously the Navier-Stokes and convection diffusion equations directly, yielding pore-scale simulations for miscible flow in several two-dimensional (2D) flow geometries
- Showed that flow reversal (echo) tests help distinguish between purely convective spreading and local ("true") mixing
- Showed that local mixing is significantly enhanced by convection and splitting around individual grains in the porous medium, but that diffusion is the fundamental mechanism of local ("true") mixing at pore scale

ACTUAL OR ANTICIPATED PROBLEMS OR DELAYS OR ACTIONS TAKEN OR PLANNED

No delays or problems have been encountered.

CURRENT STATUS (NOVEMBER 2006)

The project is beginning its final year. Milestones have been met as scheduled

FUNDING

This project was selected in response to DOE's Office of Fossil Energy Research and Development solicitation DE-PS2604NT15450-3F.

Project Start: October 1, 2004

Project End: September 30, 2007

DOEContribution: $800,000

PerformerContribution: $200,000 (20% of total)

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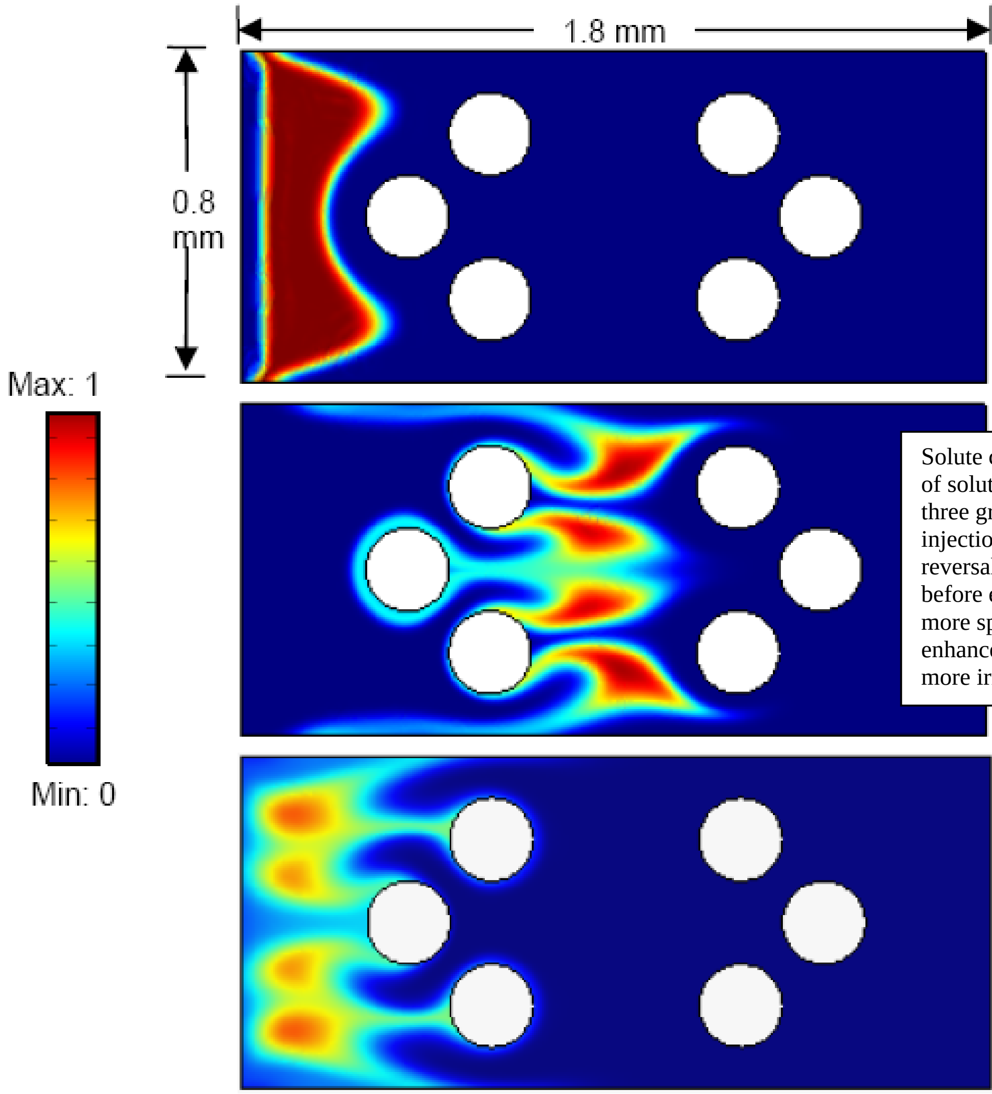
DESCRIPTION OF ANY TECHNOLOGY TRANSFER ACTIVITIES

Publications

Jha, R. K., A. K. John, S. L. Bryant and L. W. Lake. (2006). Flow reversal and mixing. 2006 SPE Annual Technical Conference and Exhibition. San Antonio, Texas, U.S.A, Society of Petroleum Engineers.



Solute concentration profiles for flow of solute slug around three grains (top) five seconds after injection, (middle) at the time of flow reversal and (bottom) five seconds before exit. More grains correspond to more splitting of solute slug and hence enhanced local mixing and more irreversibility.

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