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

Project DE-FC26-03NT15534

SEMI-ANNUAL REPORT

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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 progress to date is meeting the expectations laid out in the project description. The apparatus and software is in place for carrying out refined experiments and simulations that will better elucidate the pore-scale influences on dispersion.

RESULTS OF WORK DURING REPORTING PERIOD

Task 1 – Micro-sensor Measurements of Pore-scale Dispersivity

The following sections summarize progress on the fabrication of nitrate microsensors in terms of (1) extending sensor lifetime using a double-layer electrode configuration, and (2) testing the new version of the sensor in laboratory soil boxes. Emphasis here is on Year 2 progress.

Double-Layer Electrodes – In an attempt to improve on the longevity of the nitrate sensor prototype developed in Year 1, we entered into a collaborative effort with organic chemistry researchers from the Weizmann Institute in Israel. Together we investigated a double-layer technique which deposits an insulating layer of bis-3.4-ethylenedi-oxyhtiophene (bis-EDOT) atop the PPy surface in an effort to retain the dopant nitrate anions which may be lost in flowing water. While the double-layer sensors remained responsive longer than the original sensors, their lifespan was unacceptably short for application to core flooding experiments.

Short-term Flow-Through Experiments - We tested the double-layer sensors in a flow-through experiment with water and found that they performed well for approximately 36 hours. Unfortunately, the same stability was not observed in soils. The reason for the sensors failure in soil flow-through experiments is not clear.

Polyvinyl Chloride-Based Nitrate Microsensors - Polyvinyl chloride (PVC) nitrate-selective membranes were fabricated using literature formulations involving a mixture of PVC, plasticizer, and quaternary ammonium ions is dissolved in tetrahydrofuran (THF). The solvent is then evaporated off the mixture, leaving a membrane behind that is selective for nitrate. We successfully replicated a recently published fabrication technique to create large-scale (8-10 mm diameter) nitrate sensors, and are working to test their characteristics and scale them down to a size suitable for the core flooding experiments.

TASK 2: Streamline Interpretation of Dispersion

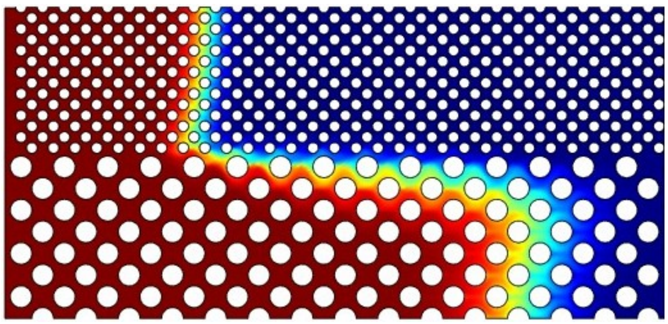
Dispersion is caused by diffusion between streamlines that can have widely varying velocities and directions within a porous media. Depending on the level of dispersion, mixing can significantly reduce the displacement efficiency of miscible gas floods, and is therefore a very important parameter for the prediction of oil recovery. The level of mixing that occurs in a reservoir, however, is still widely debated and is the focus of this research.

Our research has focused on two approaches. First, we focused on the pore scale to better understand the origins of both longitudinal and transverse dispersion and to determine how mixing is affected by various causes of dispersion. Second, we focused on how to upscale both permeability and dispersion for use in numerical simulation. This last topic will also be the focus of all future research.

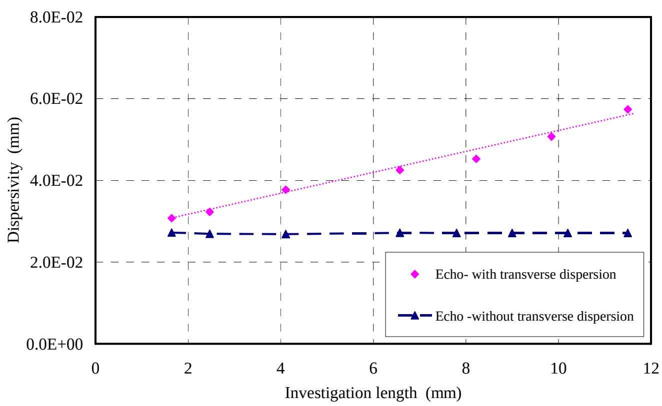
Pore-scale simulations:

Our pore-scale simulation studies show that longitudinal dispersion from echo tests in parallel layers are scale-dependent when there is transverse dispersion between layers (Fig. 1). We also show that local transverse mixing for the cases considered decreases with increasing distance in the flow direction until it reaches a constant value.

The reason for the decrease is likely the result of the location of the injection source in front of a grain boundary (Fig. 2). The transverse dispersion magnitude depends on the medium configuration. 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. We also show that measured dispersivity is greater for 3D pore-scale simulations than for 2D ones likely the result of greater surface contact between fluid and grains in 3D.



(a)



(b)

Fig. 1– Longitudinal dispersion as measured from pore-scale simulations of echo tests using COMSOL. a) Simulation concentrations with transverse dispersion between parallel layers. b) Comparison of measured dispersivity vs. distance traveled during echo test for a porous media with and without transverse dispersion caused by diffusion. A no flow barrier is between the layers in the case of no transverse dispersion.

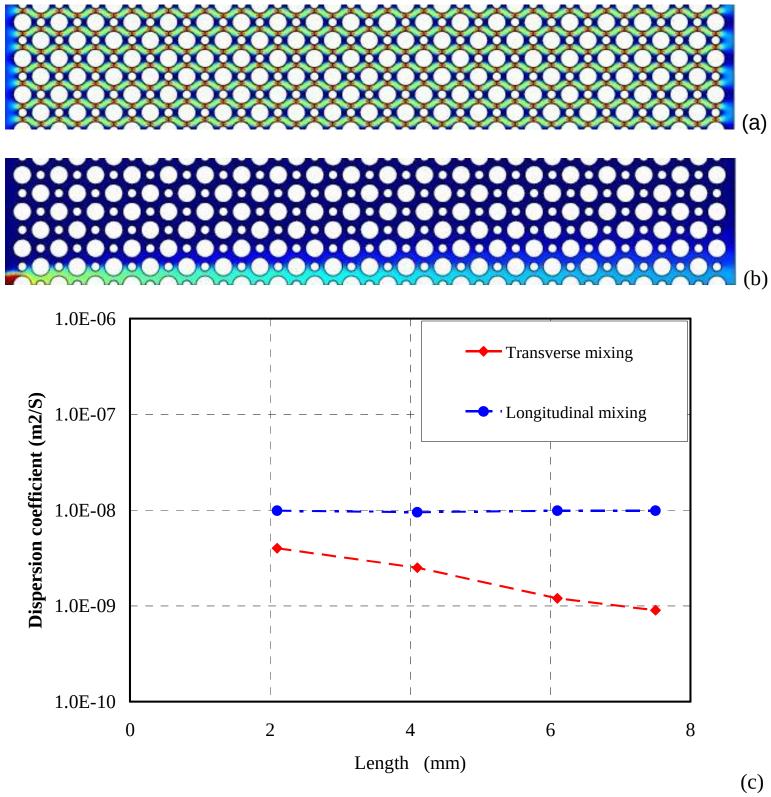


Fig. 2 – Calculation of transverse and longitudinal dispersion from COMSOL simulations of a homogeneous porous media using a known analytical solution. a) Velocity profile. b) Concentration profile. c) Calculated transverse and longitudinal dispersion for 2D homogeneous porous media. Note that because the concentration profiles are symmetric with respect to length, only half of the pore model is shown.

Modeling tracer dispersion in layered flow using particle tracking

Particle tracking simulations of tracer dispersion in layered flow shows that diffusion, aided by convection, results in enhanced levels of spreading. Pure convection can also cause such spreading but it can be distinguished from dispersive mixing by observing the change in spreading on flow reversal. Purely convective spreading is completely reversible whereas dispersive spreading is not. The results of this section form part of an SPE publication (Jha et al, 2006).

Development of 3D particle tracking code

A particle tracking code was written to perform calculations using a velocity field given on a three dimensional, cartesian grid. This velocity field is computed by solving the flow equations on the same domain under single phase, steady state, incompressible flow conditions. The velocity at each location is computed based on linear interpolation using the velocities available at the faces. 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 code was compared against a set of known analytical solutions with good agreement:

a. 1D Convection-Diffusion equation for slug injection
b. 2D Convection-Diffusion equation for slug injection
c. Taylor's dispersion for flow between parallel plates

Simulation of transport in three dimensional heterogeneous reservoirs
The code has been tested for cases in three dimensions with stochastically generated heterogeneous permeability fields. Model sizes of upto one million cells have been simulated. The results qualitatively agree with predictions based on stochastic-spectral theory for zero diffusion cases for moderate heterogeneity (Dykstra-Parsons coefficient of less than 0.5). But they point out to the significance of boundary effects in delaying the transition to asymptotic behavior. With no diffusion, this spreading is fully reversible. With diffusion, the spreading progressively becomes irreversible with distance traveled. Echo dispersion values for large distances traveled are comparable in magnitude to transmission values.

Investigation of Local Mixing and its Influence on Core Scale Mixing Behavior
Local solute concentration measurements in a sand pack in miscible displacement experiments show non-zero local (pore scale) mixing. Pore scale simulation studies in model two dimensional (2D) porous media show that diffusion is the fundamental mechanism of local mixing. Diffusion, even though small in magnitude, is enhanced in pore space by local velocity gradients and becomes an efficient mixing mechanism. Local mixing caused by diffusion is independent of flow direction and that makes mixing irreversible. On the other hand, pure convective spreading in absence of diffusion is reversible.

In order to study mixing in a realistic porous medium and to explain core scale mixing behavior quantitatively, we can track movement of a swarm of solute particles through a dense, three dimensional random pack of spheres. A dense random pack of spheres is a reasonably realistic model of porous media. The geometry and topology of the pore space determines important macroscopic properties of the medium such as permeability and dispersivity and cannot be neglected for predicting core-scale properties.

We prepared a hydraulically equivalent network model of a computer generated dense random packing of spheres. This model conserves the pore geometry and explicitly accounts for connection of a pore with its unique set of neighbors. Flow rate in each pore throat is calculated by applying mass conservation at each pore. The permeability of this realistic network is 30% less than that of an unrealistic network with randomly distributed flow properties.

TASK 3 - Impact on Field Miscible Gas Floods

Upscaling dispersivity from laboratory to field scale
Upscaling techniques are often required to coarsen the geological models to provide values for large grid blocks in compositional or black oil simulation. We developed a code to do flow and transport modeling of the fine grid data to find its equivalent coarse grid dispersivity and permeability, which should be used in reservoir simulation. At the fine scale we use very small values of dispersivity. As the upscaling proceeds, however, larger values of dispersivity are needed. The research upscales both

permeability and dispersion simultaneously because permeability affects the velocity variations within the porous media. Our results to date show that the magnitude of dispersivity depends significantly on the correlation length and standard deviation of the permeability, that is, reservoir heterogeneity.

Dispersivity grows when the size of the equivalent grid block is increased. Numerical dispersion, which is also present in the simulations, does impact the upscaling process. Figure 3 shows the upscaling procedure from the fine grid scale with over 3600 grid blocks to only 36 coarse grid blocks. The results do not match exactly because dispersion in each upscaled grid block is nonFickian.

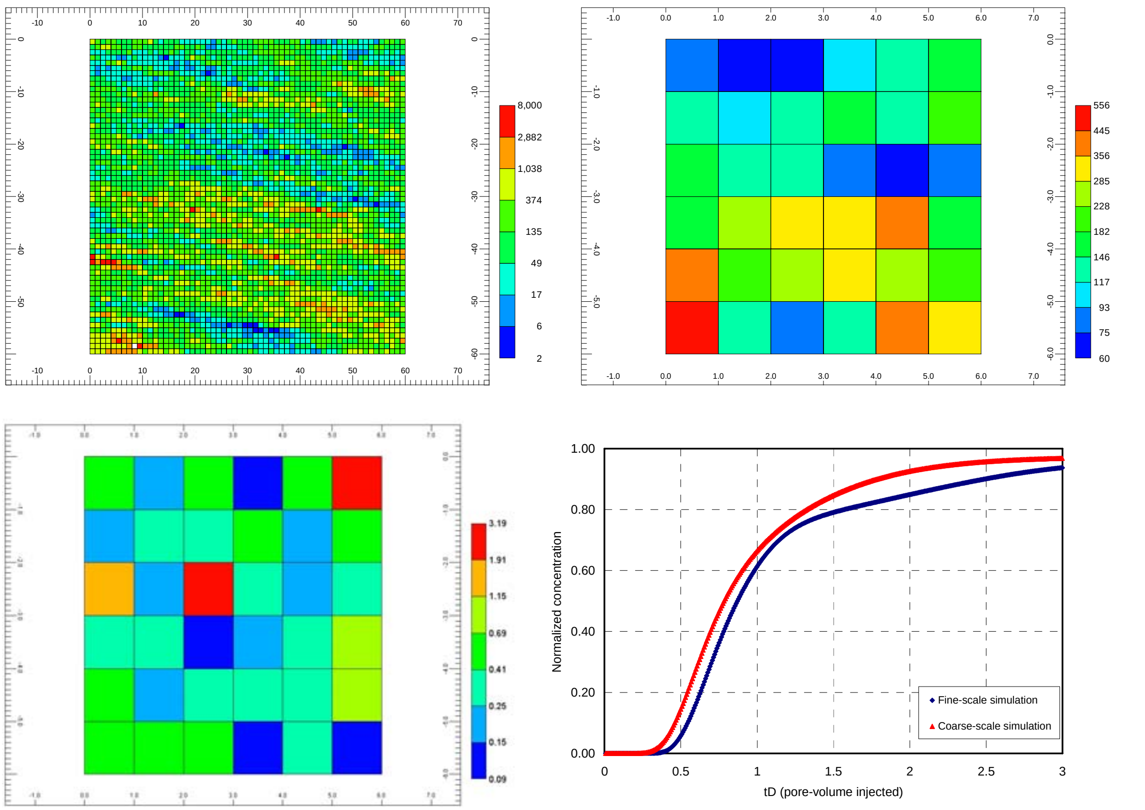


Fig. 3 – Example of upscaling permeability and dispersion for a porous media with a correlation length that is 10% of the total reservoir length. a) Fine-scale permeability distribution, b) Upscaled permeability distribution, c) Upscaled dispersivity distribution (fine-scale dispersivity input is 0.05 m), d) Fine-scale and coarse-scale single phase tracer transport simulation comparison.

APPROACH

Sensor Development

A promising technique proposed by Sutton et al. (1999) involves creating covalently bonded triallyldecylammonium nitrate plus mediators in a Krynac (polyacrilonitrilebutadiene) polymer. The reagents for this nitrate-selective membrane are dissolved in tetrahydofuran (THF) and lyophisilized over phosphorous pentoxide in a vacuum oven at room. Macroelectrode sensors of this type have been successfully tested in rivers and agricultural drainage canals for periods exceeding 6 months.

Modeling

To incorporate fundamental understanding of dispersion at the pore or "quantum" scale (streamtubes through single pores) with previous model development, we model flow with streamlines and impose random jumps between streamlines to emulate diffusion. This combination should be able to encompass the end-members of purely streamline flow and well mixed flows, as well as flows in between such a variation of the famous Taylor mixing effect. We will use the streamline-random jump to interpret the local dispersion experiments. This interpretation would, as a best case, entail a fully three-dimensional distribution of the flow velocities within the medium.

To establish a baseline for the streamline modeling, we used FEMLAB to simulate tracer flow in reconstructed 2D porous media and in model 2D grain packs.

RESULTS AND DISCUSSION

Mixing inside a pore body ("local mixing") is demonstrated by pore level simulation studies. It has been found that diffusion, even though small, is the fundamental mechanism of local mixing. Convection and splitting of solute front around the sand grains play a role in enhancing local mixing by increasing the contact area between large and small concentrations. Local mixing does not depend on the direction of flow and therefore makes mixing irreversible.

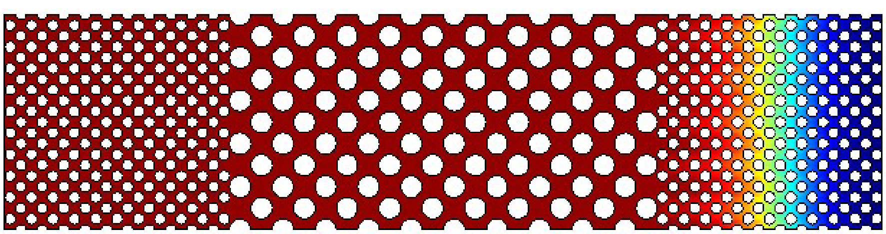


Fig. 4. The simulated movement of a tracer front through a simple heterogeneous medium above shows the nonlocal nature of dispersion. The observed dispersivity increases by a factor of two as the front moves from the fine beads (leftmost section) into the coarse beads (middle section), but it does *not* decrease when the front enters the fine beads in the rightmost section.

Modeling local vs overall dispersion

Particle tracking simulations of tracer dispersion in layered flow shows that diffusion, aided by convection, results in enhanced levels of spreading. Pure convection can also cause such spreading but it can be distinguished from dispersive mixing by observing the change in spreading on flow reversal. Purely convective spreading is completely reversible whereas dispersive spreading is not.

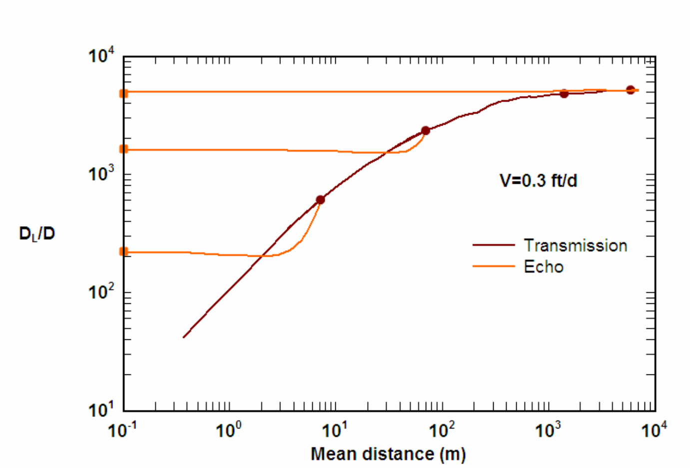


Fig. 5. Evolution of normalized dispersion coefficient with mean distance travelled in transmission(forward flow) and echo (reverse flow) directions for tracer injected in a layered flow field. Dispersion coefficient slowly increases and reaches an asymptotic limit at which spreading is irreversible. Reversed flow (Echo) dispersion values increase with penetration distance. Diffusion coefficient (D) is 1E-9 m^2/s.

Application of carbon fiber microsensors

Conducting organic polymer-based nitrate ion selective electrodes (ISEs) were fabricated at sizes ranging from 7 to 100 microns in diameter. These prototypes were successfully tested in batch systems with small reference electrode (2 mm diameter). The reference electrode was miniaturized to make it optimal for use with micron-scale ISEs in porous media tests. Column tests with the new sensors were successfully completed, and data analysis is underway.

CONCLUSION

Electrodes using a double layer of insulator and dopant were constructed and tested. They showed better performance than the previous prototypes (longer sensitivity to nitrate anion concentrations in solution) but their lifespan (~36 hrs) is still too short to be convenient for some columnflood and many field applications. An alternative method of sensor synthesis (evaporation of a solvent from a PVC+plasticized+ammonium mixture) appears promising and work to scale them down to size appropriate for coreflood applications in in progress.

The most fundamental conclusion from the modeling and simulation work is that dispersivity is the convolution of boundary conditions (the flow field imposed upon the porous medium) and the heterogeneity of the porous medium itself. The echo test, in which the simulated flow field is reversed after a pulse of tracer is transported a certain distance into the medium, proves a valuable method of evaluating the relative contributions of boundary conditions (flow field) and heterogeneity of the medium. A realistic and physically representative grain scale flow network has been calculated for a model porous medium (dense random packing of equal spheres) spanning several thousand grains. This is an important milestone for performing *a priori* predictions of the effect of variability of the flow field at the pore scale on dispersivity.

MILESTONES NOT MET DURING REPORTING PERIOD AND REASONS WHY.

The key milestones for the column floods have all been met. The milestones for the streamline have also been met.

COST AND SCHEDULE STATUS

The project is proceeding as planned regarding both expenditures and objectives.

SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

We fabricated simple but novel two-conductor microsensors that allow measurement of conductivity of an aqueous solution at the scale of a few pores (a few hundreds of microns). We used these sensors to obtain novel measurements of local concentration histories in classical miscible displacement in sand columns. The measurements showed that dispersivity at the local scale was very similar both quantitatively and qualitatively to dispersivity at the core scale (tens of cm). We carried out high-resolution FEMLAB simulations of Navier-Stokes flow and advection-diffusion transport equations in 2D model porous media (an irregular geometry from a micromodel and a loose array of disks) in order to establish a baseline for the expected behavior of streamline models. The idea is to find analytically whether fine scale behavior (diffusion, "jumping" of solute particles between streamlines) or larger scale behavior (intersection of different streamlines originating at different locations in the core) is the cause of dispersion observed at the pore and core scales.

ACTUAL OR ANTICIPATED PROBLEMS OR DELAYS OR ACTIONS TAKEN OR PLANNED

No delays or problems have been encountered.

DESCRIPTION OF ANY TECHNOLOGY TRANSFER ACTIVITIES ACCOMPLISHED

Jha, R., Bryant, S., Lake, L. and John, A. "Investigation of Pore-Scale (Local) Mixing" SPE 99782, *Proceedings of 2006 SPE/DOE Symposium on Improved Oil Recovery* held in Tulsa, Oklahoma, U.S.A., 22–26 April 2006.

Jha, R. K., John, A. K., Bryant, S. L. and Lake, L. W. "Flow reversal and mixing" SPE 103054, *Proceedings of 2006 SPE Annual Technical Conference and Exhibition* held at San Antonio, Texas, U.S.A., 24–27 September 2006.