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Our research under this grant has focused on three-dimensional numerical simulations, as well as on computational linear stability analysis. In the following, our main results for each of those areas will be described separately. In addition, copies of reprints are attached with this report.

1. High resolution numerical simulations

1.1 Three-dimensional miscible displacement simulations in homogeneous porous media with gravity override

In this part of the project, high accuracy, three-dimensional numerical simulations of miscible displacements with gravity override in homogeneous porous media were carried out for the quarter five-spot configuration. Special emphasis is placed on describing the influence of viscous and gravitational effects on the overall displacement dynamics in terms of the vorticity variable. Even for neutrally buoyant displacements, three-dimensional effects are seen to change the character of the flow significantly, in contrast to earlier findings for rectilinear displacements. At least in part this can be attributed to the time dependence of the most dangerous vertical instability mode. Density differences influence the flow primarily by establishing a narrow gravity layer, in which the effective Peclet number is enhanced due to the higher flow rate. However, buoyancy forces of a certain magnitude can lead to a pinch-off of the gravity layer, thereby slowing it down. Overall, an increase of the gravitational parameter is found to enhance mostly the vertical perturbations, while larger Peclet number values act towards amplifying horizontal disturbances. The asymptotic rate of growth of the mixing length varies only with Peclet number. For large Peclet numbers an asymptotic value of 0.7 is observed. A scaling law for the thickness of the gravity layer is obtained as well. In contrast to immiscible flow displacements, it is found to increase with the gravity parameter.

1.2 Variable density, miscible displacements in three-dimensional heterogeneous porous media

Here the vorticity interaction mechanisms governing miscible displacements in three-dimensional heterogeneous porous media are investigated by means of detailed simulations in the regimes of viscous fingering, channeling, and resonant amplification. The computational results for spatially periodic and random permeability distributions are analyzed in detail with respect to the characteristic wavenumbers and norms associated with the individual vorticity components. This enables the identification of the mechanisms dominating specific parameter regimes. Nominally axisymmetric displacements such as the

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present quarter five-spot configuration are particularly interesting in this respect, since some of the characteristic length scales grow in time as the front expands radially. This leads to displacement flows that can undergo resonant amplification during certain phases, while being dominated by fingering or channeling at other times. The computational results also provide insight into the effects of density-driven gravity override on the interactions among these length scales. While this effect is known to play a dominant role in homogeneous flows, it is suppressed to some extent in heterogeneous displacements, even for relatively small values of the heterogeneity variance. This is a result of the coupling between the viscous and permeability vorticity fields in the viscous fingering and resonant amplification regimes. In the channeling regime, gravity override is somewhat more effective because the coupling bewteen the viscous and permeability vorticity fields is less pronounced, so that the large scale structures become more responsive to buoyancy effects.

2. Computational linear stability analysis

2.1 Linear stability of radial displacements in porous media: Influence of velocity-induced dispersion and concentration-dependent diffusion

A parametric study is conducted in order to investigate the influence of (a) velocity dependent dispersion, and (b) concentration dependent diffusion on the stability of miscible porous media displacements in the radial geometry. Numerical solutions for the base concentration profile demonstrate that velocity induced dispersion dominates for short times and large Peclet numbers. For large times, the growth rates approach those obtained when only molecular diffusion is taken into account. Concentration dependent diffusion coefficients are seen to modify the mobility profiles of the base flow, and to shift the eigenfunctions into more or less viscous environments. This results in a destabilization for nearly all Peclet values and mobility ratios.

2.2 Radial source flows in porous media: Linear stability analysis of axial and helical perturbations in miscible displacements

Linear stability results are presented for axial and helical perturbation waves in radial porous media displacements involving miscible fluids of constant density. A numerical eigenvalue problem is formulated and solved in order to evaluate the relevant dispersion relations as functions of the Peclet number and the viscosity ratio. In contrast to the constant algebraic growth rates of purely azimuthal perturbations [C.T. Tan and G.M. Homsy, Phys. Fluids 30, 1239 (1987)], axial perturbations are seen to grow with a time-dependent growth rate. As a result, there exists a critical time up to which the most dangerous axial wavenumbers are larger, and beyond which the most dangerous azimuthal wavenumbers have higher values. This raises the possibility that early on, the smaller flow scales appear in the axial direction, whereas the later flow stages are dominated by smaller azimuthal features. By rescaling the axial wavenumber, the explicit appearance of time can be eliminated. The maximum growth rate of axial perturbations, as well as their most dangerous and cutoff wavenumbers, are seen to increase with the Peclet number and the viscosity ratio. The most dangerous wavenumber is observed to shift towards the lower end of the spectrum as the Peclet number increases. With increasing viscosity contrast, it first moves towards the lower part of the spectrum, only to shift towards the higher end later on. In the limit of large Peclet numbers, asymptotic solutions are obtained for the growth of axial disturbances. Numerical solutions of the full eigenvalue problem generally show good agreement with these asymptotic solutions for large Peclet numbers. Over the entire range of wave vector directions between the purely axial and azimuthal extrema, helical waves display an approximately constant maximum growth rate. The wavenumber of maximum growth as well the maximum growth rate of helical waves can be evaluated from the corresponding purely azimuthal and axial problems. This suggests that in three-dimensional flows the nature of the initial conditions plays an important role.