74

SCALE-UP OF MISCIBLE FLOOD PROCESSES
Contract No. DE-FG22-92BC14852

Department of Petroleum Engineering
Stanford University

Project Status

Two-dimensional (2D) calculations are routinely used to investigate the relative importance of gravity segregation and viscous fingering. However, there has been no systematic investigation whether 2D calculations accurately represent three-dimensional (3D) flow behavior. 2D and 3D computations by a particle-tracking technique are compared for unstable displacements in homogeneous porous media, with and without gravity. The particle-tracking technique has been shown previously to reproduce accurately experimental observations of viscous fingering in 2D flows. In addition, calculations in 2D of the effects of gravity and viscous fingering are also reproduced well. Thus, there is considerable evidence that the computational approach used here reproduces accurately the physical phenomena under investigation.

Detailed comparisons of many 2D and 3D displacement calculations with very fine grids ($128\times64\times32$) indicates that fingering patterns are quite similar in 2D and 3D if gravity effects are absent. When a significant density difference exists, however, 2D flow can be very different from 3D flow. Thus, comparison of 2D and 3D simulations of unstable displacements leads to the following conclusions:

1. In the *absence of gravity*, 2D and 3D simulations predict similar finger dimensions and averaged concentration profiles. Breakthrough times are always earlier in 3D, but 2D and 3D systems display similar recovery behavior.

2. When gravity effects are present, the flow behavior can be quite different in 2D and 3D. The transition from flow dominated by gravity to flow dominated by viscous fingering occurs over a wider range of $R_{v/g}$, (ratio of viscous to capillary forces), in 3D flows. The concentration profiles and recovery in the transition region obtained from 2D flows show significant differences from those obtained from 3D flows.

3. For gravity-dominated ($R_{v/g} < 1$) or fingering-dominated flows, 2D predictions of average displacement performance agree well with 3D calculations.

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Introduction

The current project is a systematic research effort aimed at quantifying the interactions of physical mechanisms that control the scaling behavior of miscible floods. Displacement performance in a miscible flood is the result of a complex set of competing and interacting mechanisms. Phase behavior is of fundamental importance because the transfer of components from the oil to the injected fluid (as in most CO_2 floods) or from the injected fluid to the oil (as in rich gas floods) can generate mixture compositions with displacement properties very different from those of pure CO_2 and original oil. In one-dimensional flow, the favorable effects of phase behavior can lead to displacement efficiencies that approach 100 %. Displacements in reservoir rocks are anything but one-dimensional, however. The rocks themselves are heterogeneous, and even if they were homogeneous, most miscible floods are subject to a hydrodynamic instability that results from displacement of oil by gas with lower viscosity. The result is nonuniform flow whether the cause is viscous fingering, reservoir heterogeneity, or, more likely, some combination of the two. When flow is nonuniform then there is the potential, at least, for crossflow between zones of fast and slow flow. Such crossflow can result from diffusion and dispersion, gravity segregation, capillary or viscous forces and would cause mixing of fluids of different composition. That mixing, in turn, causes mixture compositions that occur during a multidimensional displacement to differ from the corresponding compositions in a one-dimensional displacement. Because composition route can strongly influence local displacement efficiency, crossflow and the resulting induced mixing will influence recovery performance in field-scale floods. The magnitude of the influence depends on the lengths over which crossflow occurs, the rate at which fluids are moved, and, of course, the phase behavior of the resulting mixtures.

The goal of this project, therefore, is to make more accurate quantitative predictions of the impact of nonuniform flow, crossflow and phase behavior in flows in heterogeneous reservoir rocks. In past reports, we have discussed the instabilities arising from unfavorable mobility ratios that occur during injection of a solvent such as CO_2.

In this report, two-dimensional (2D) and three-dimensional (3D) computations by a particle-tracking technique are compared for unstable displacements in homogeneous porous media, with and without gravity. In homogeneous porous media without gravity, 2D fingering patterns and the length of the transition zone are nearly the same as those obtained in 3D displacements. When gravity is added, however, calculated gravity tongues and fingering patterns can be very different when viscous and gravity forces are of comparable magnitude.

We summarize results obtained by Ph.D. student Hamdi Tchelepi concerning 2D and 3D fingering in homogeneous media, and we compare displacements with and without gravity segregation. The computations show conclusively that there are some situations in which 2D simulations reproduce 3D behavior well and others for which they do not.

Homogeneous Domains

Displacements without Gravity

Fig. 1 is a comparison with a corresponding 2D displacement with horizontal and vertical slices through the 3D porous medium. Fig. 1 shows that fingers have penetrated slightly farther in the 3D displacement, but overall, fingers clearly have dimensions that are nearly the same, whether the flow is 2D or 3D. Furthermore, in the absence of gravity, the numbers of fingers and their widths are essentially equal in the horizontal and vertical directions. That result is not surprising because the dimensions of fingers depend on the level of transverse dispersion, mobility ratio and flow length, factors that act similarly in 2D and 3D.

Another comparison of 2D and 3D fingering is given in Fig. 2 which compares transversely averaged concentration profiles for 2D and 3D simulations for M = 30 (M = mobility ratio, μ_o/μ_w). In 2D flow, fingering is recorded as noticeable kinks and dips in the one-dimensional profiles of Fig. 2. The profiles obtained from 3D simulations are smoother. Fig. 2 shows that overall, the one-dimensional concentration profiles are remarkably similar in 2D and 3D.

There are some differences, however. The leading edge of the transition zone travels slightly faster in 3D flow, though the total amount of solvent associated with the separation between the leading edges in 2D and 3D flow is small. Fig. 1 indicates that the leading region of low average concentration results from a small number of fingers that have penetrated slightly farther than the rest of the pack. More fingers lead to a higher degree of nonlinear interactions. Coalescence, which is frequently observed when dispersion is anisotropic and almost absent when dispersion is isotropic[2], coupled with shielding[3] enhances the growth rate of the dominant fingers. We speculate that the faster penetration of the leading edge observed in 3D is the result of an enhancement of coalescence and shielding brought about by the increased competition among more numerous fingers. The faster penetration in 3D leads to earlier breakthrough in all 3D simulations for all the mobility ratios investigated.

The 2D simulations summarized in Fig. 2 show several local concentration maxima. Those maxima are associated with the tips of individual fingers (see Fig. 1). Fingers spread at their tips[3, 4, 5], and hence, just behind the tips of a finger the area occupied by a fingers is a smaller fraction of the flow area, and the recorded average concentration therefore can be slightly lower. Fig. 1 indicates that the amount of spreading is essentially the same in both 2D and 3D fingers, so it is the averaging over a larger number of fingers, which have penetrated differing distances, that eliminates the maxima. A maximum could also be the signature of a sideways attack as the tip of a shorter finger coalesces with the body of a longer one. The larger sample being averaged in 3D eliminates those maxima from the one dimensional profiles as well.

Displacements with Gravity

When effects of gravity transverse to the mean flow are included in the simulation, whether 2D or 3D displacements are similar depends on the relative importance of viscous and gravity forces. In both 2D and 3D displacements, of course, there is a competition between viscous forces that drive the hydrodynamic instability and buoyancy forces that attempt to create a gravity tongue.

That transition is illustrated in Fig. 3 for 2D flow. Previous investigators have used various forms of a dimensionless group to describe the relative importance of viscous forces and gravity forces[14-19]. Here we use the definition of Fayers and Muggeridge[8],

$$R_{v/g} = 2\frac{\overline{v} \triangle \mu}{\Delta \rho g k_z}\frac{H}{L} \tag{1}$$

The onset of viscous fingering occurs at about $R_{v/g} \approx 1$. When gravity effects were included, we used a density difference, $\Delta\rho = 0.2g/cm^3$, a permeability, k, of 100 Darcy which is also the geometric mean of the heterogeneous domains. The oil viscosity, μ_o, was 1 cp. The viscosity of solvent, μ_s, was varied for a particular mobility ratio, $M = \mu_o/\mu_s$, and the average Darcy velocity, $\overline{v}$, was varied to obtain different $R_{v/g}$ values. The height, H, and width, W, of the 3D domains were always equal. Unless explicitly stated otherwise, the simulations were for systems with L/H of 4. We report the values of all the parameters involved in $R_{v/g}$ that were used in the simulations because extensive simulations indicate that when both viscous and gravity forces are significant, no one version of $R_{v/g}$ captures all of the phenomena at work. The major point of concern is the presence of L/H as a multiplier in $R_{v/g}$. L/H appears as a coefficient elsewhere in the governing equations and can not be varied independently.

As Fig. 3 shows for 2D flow, at low values of $R_{v/g}$, a significant gravity tongue develops, which leads to early breakthrough of the injected fluid. As viscous forces become more important ($R_{v/g}$ increases), the gravity tongue recedes, giving way to viscous fingering which result in improved coverage and delayed breakthrough. In 2D displacements, Fig. 3 also indicates that for values of $R_{v/g}$ greater than about 10 for M = 30 and L/H = 4, gravity segregation has a small effect on the distribution of fluids and breakthrough time. For $R_{v/g} < 1$, gravity segregation dominates the flow[8]. Experimental observations confirm the existence of the transition described[6, 9, 10].

The effects of the gravity transition are summarized in Fig. 4, which reports simulation results of breakthrough times for 2D displacements at three mobility ratios, M = 10, 30 and 50. Clearly, breakthrough recovery declines as M increases and/or as $R_{v/g}$ decreases. Fig. 4 also shows the effect of the gravity transition for 3D displacements with M = 30. Gravity segregation causes significantly earlier breakthrough in 3D than in 2D at the same value of $R_{v/g}$ and M. Fig. 4 also indicates that when flow is 3D, gravity segregation has significant impact on breakthrough time at values of $R_{v/g}$ an order of magnitude larger than those at which 2D flow is dominated by viscous fingering.

We offer the following explanation for the difference between 2D and 3D displacement behavior under the influence of gravity. In unstable 2D flow, (see Fig. 3), at a sufficiently high value of $R_{v/g}$, the effect of gravity is to cause upward flow of injected fluid within the fingers and downward flow of the resident, more viscous fluid, between the fingers. In 2D, that flow can only occur in the plane, and hence it must cause mixing of the two fluids. The displacements at $R_{v/g} = 1$ and 2 in Fig. 3 show clear evidence of that mixing, for example. That mixing reduces the local contrasts in viscosity and density, thus changing the balance between the horizontal and vertical driving forces.

In a 3D displacement, however, vertical flow need not take place in a single plane. Instead, downward flow of the heavy, more viscous fluid can occur between the fingers. Less mixing takes place, the viscosity and density contrasts remain higher than in 2D, and hence,

segregation remains important at larger values of $R_{v/g}$. Fig. 5 further illustrates the enhanced vertical flow in 3D for $R_{v/g} = 20$. The corresponding 2D flow shows no evidence of a gravity tongue. In 3D flow, a fingered gravity tongue forms, and several fingers in various vertical slices show some upward movement with minimal mixing and dilution.

Fig. 4 indicates that whether the flow is 2D or 3D, at sufficiently low values of $R_{v/g}$, the flow is dominated by gravity override, and that at sufficiently high values, viscous fingering dominates. Thus, at either limit when gravity or viscous fingering dominates, 2D and 3D flows display similar behavior. In the transition region, which spans a wider range of $R_{v/g}$ in 3D, displacements in 2D and 3D flow yield significantly different distributions of fluid in the porous medium.

The effect of the interplay of viscous and gravity forces on recovery in 2D and 3D flows is illustrated in Fig. 6, which shows recovery curves for 2D and 3D simulations at $R_{v/g} = 5$ for systems with L/H = 4 and 16. Differences between 2D and 3D recovery curves are small for the L/H = 4 case. However, the recovery curves when L/H = 16 differ substantially for this value of $R_{v/g}$, which is in the range where the 2D flow is fingering-dominated for the L/H = 16 system, but the 3D flow is still strongly affected by gravity segregation. Thus, 2D calculations can yield inaccurate predictions when $R_{v/g}$ is in the transition region and L/H is large, as it is likely to be in field-scale flows.

Discussion

The examples given here show that unstable displacements in 3D homogeneous media can be very different from displacements in 2D porous media, especially when the effects of gravity are also considered. Thus, use of 3D simulations to assess the relative importance of viscous and gravity forces is desirable, though it is clear that such simulations will continue to be limited by the computation time required and by the availability and resolution of 3D reservoir description data. The results presented here suggest that at the very least, some 3D simulations should be performed to assess the uncertainty that arises if 2D cross sections are used to select injection rates, for example. The particle tracking technique used here is one relatively efficient approach that can be used to perform such an assessment.

Conclusions

Comparison of 2D and 3D simulations of unstable displacements in homogeneous porous media leads to the following conclusions:

1. In the absence of gravity, 2D and 3D simulations predict similar finger dimensions and averaged concentration profiles. Breakthrough times are always earlier in 3D, but 2D and 3D systems display similar recovery behavior.

2. The transition from flow dominated by gravity to flow dominated by viscous fingering occurs over a wider range of $R_{v/g}$ in 3D flows. The concentration profiles and recovery in the transition region obtained from 2D flows show significant differences from those obtained from 3D flows.

3. For gravity-dominated ($R_{v/g} < 1$) or fingering-dominated flows, 2D predictions of average displacement performance agree well with 3D calculations.

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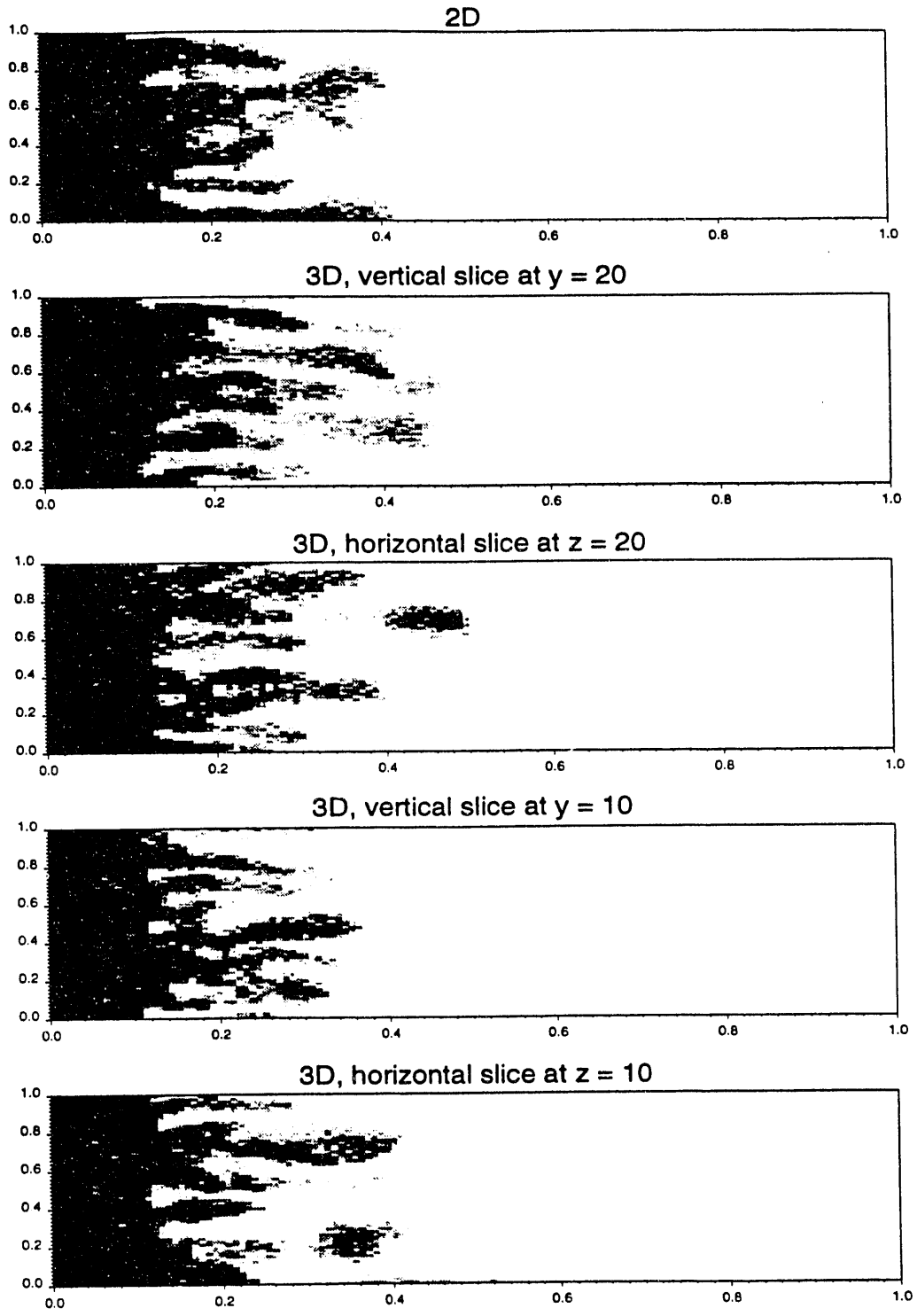

Figure 1: Comparison at 0.2 PVI of 2D and 3D displacements with M = 30 in a homogeneous porous medium in the absence of gravity

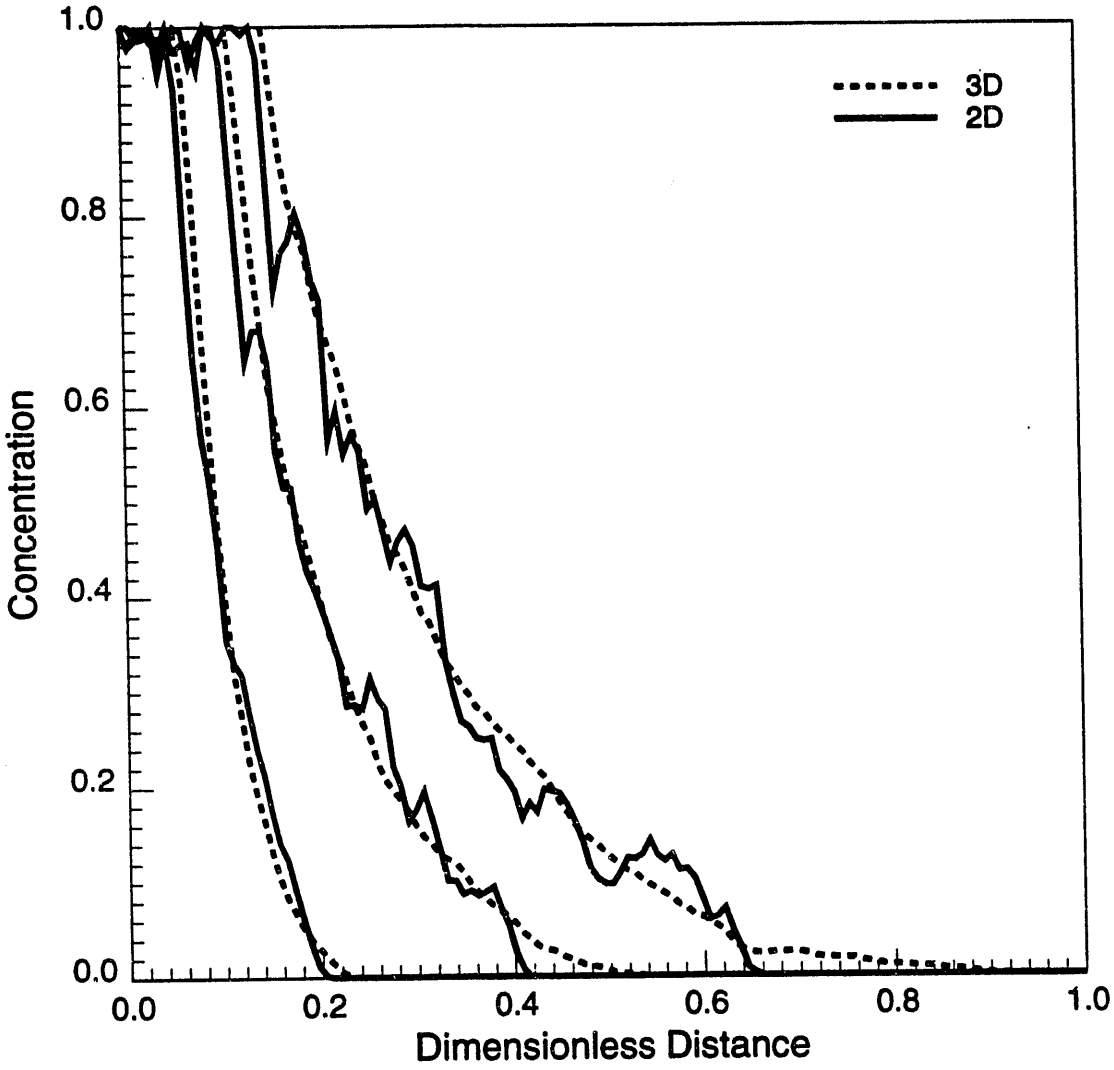

Figure 2: Comparsion of transversely averaged concentrations of injected fluid in 2D and 3D displacements with M = 30 in a homogeneous porous medium in the absence of gravity.

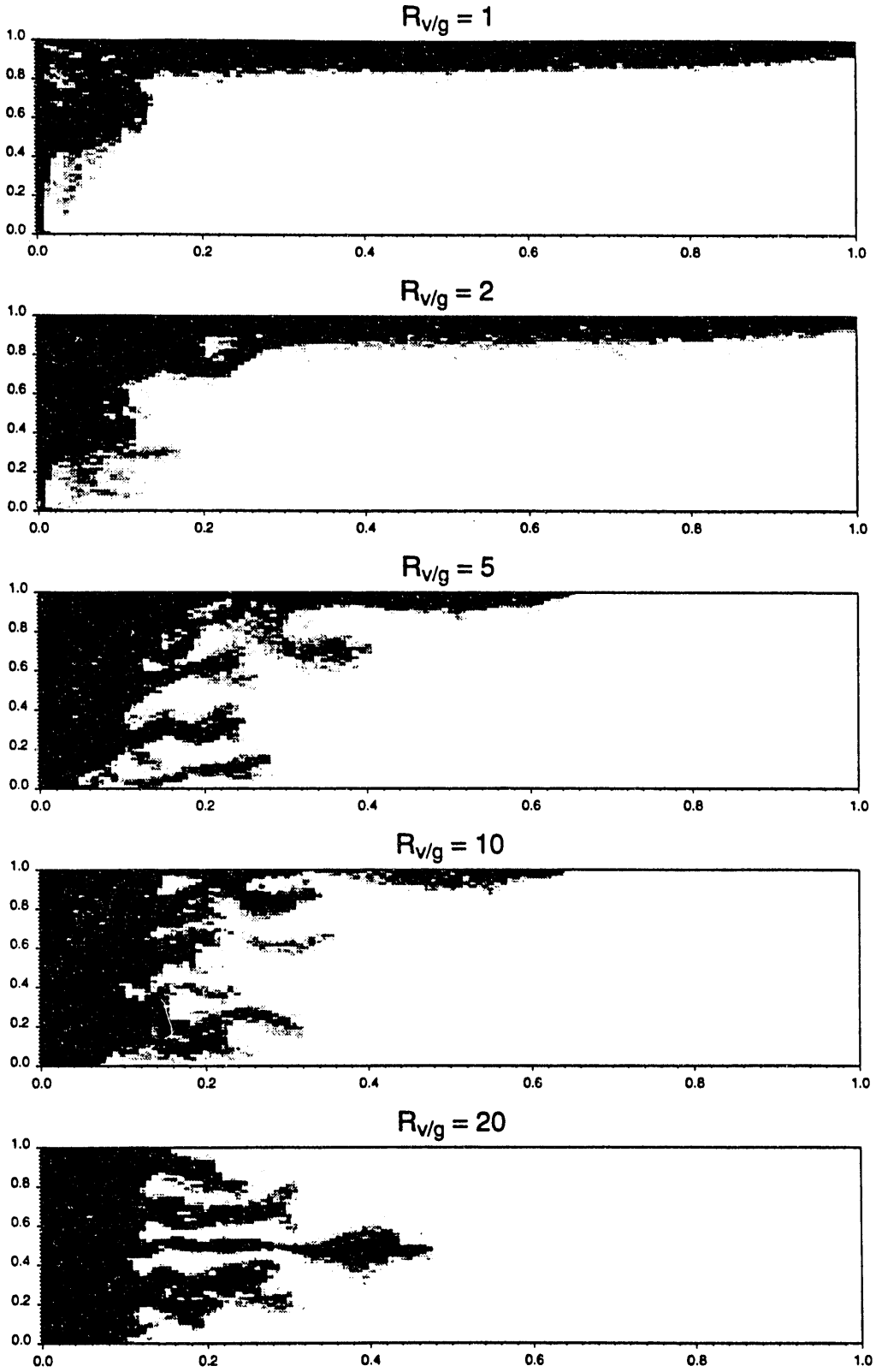

Figure 3: Effect of viscous to gravity ratio, $R_{v/g}$, in 2D displacements for M = 30 at 0.2 PVI.

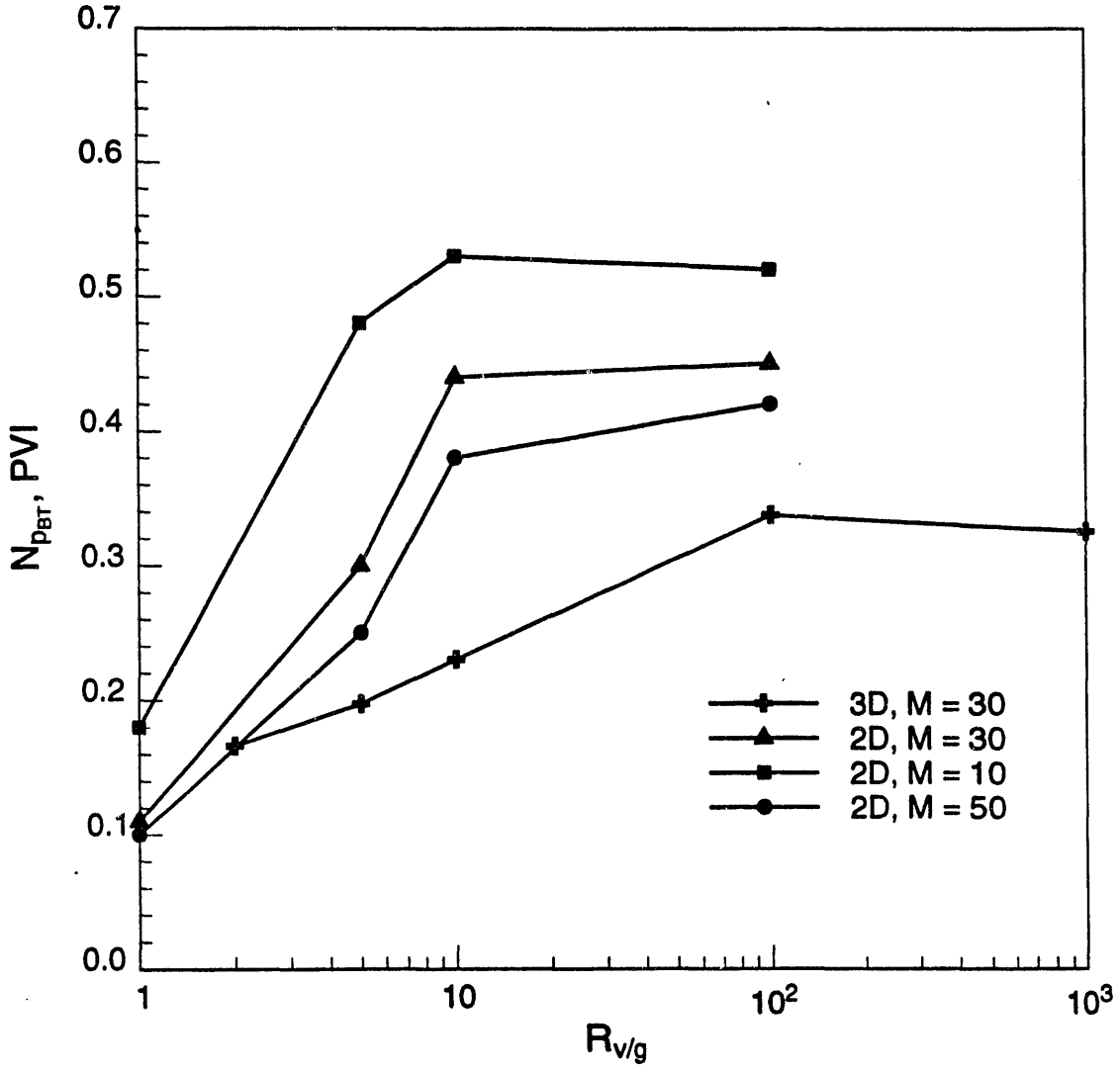

Figure 4: Effect of viscous to gravity ratio, $R_{v/g}$, on breakthrough recovery for 2D and 3D displacements when L/H = 4.

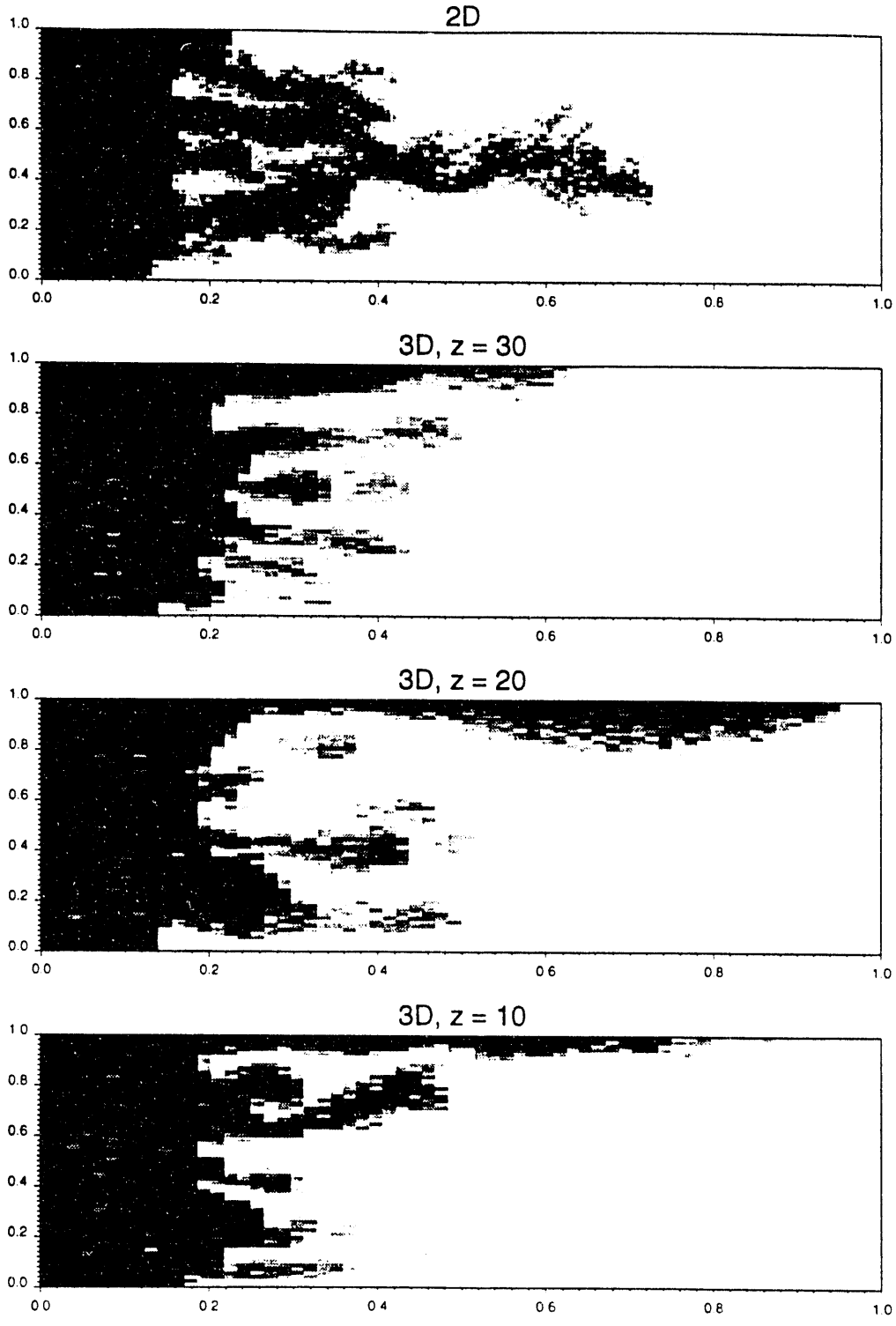

Figure 5: Comparison at 0.3 PVI of 2D and 3D displacements with M = 30 and $R_{v/g}$ = 20 in a homogeneous porous medium.

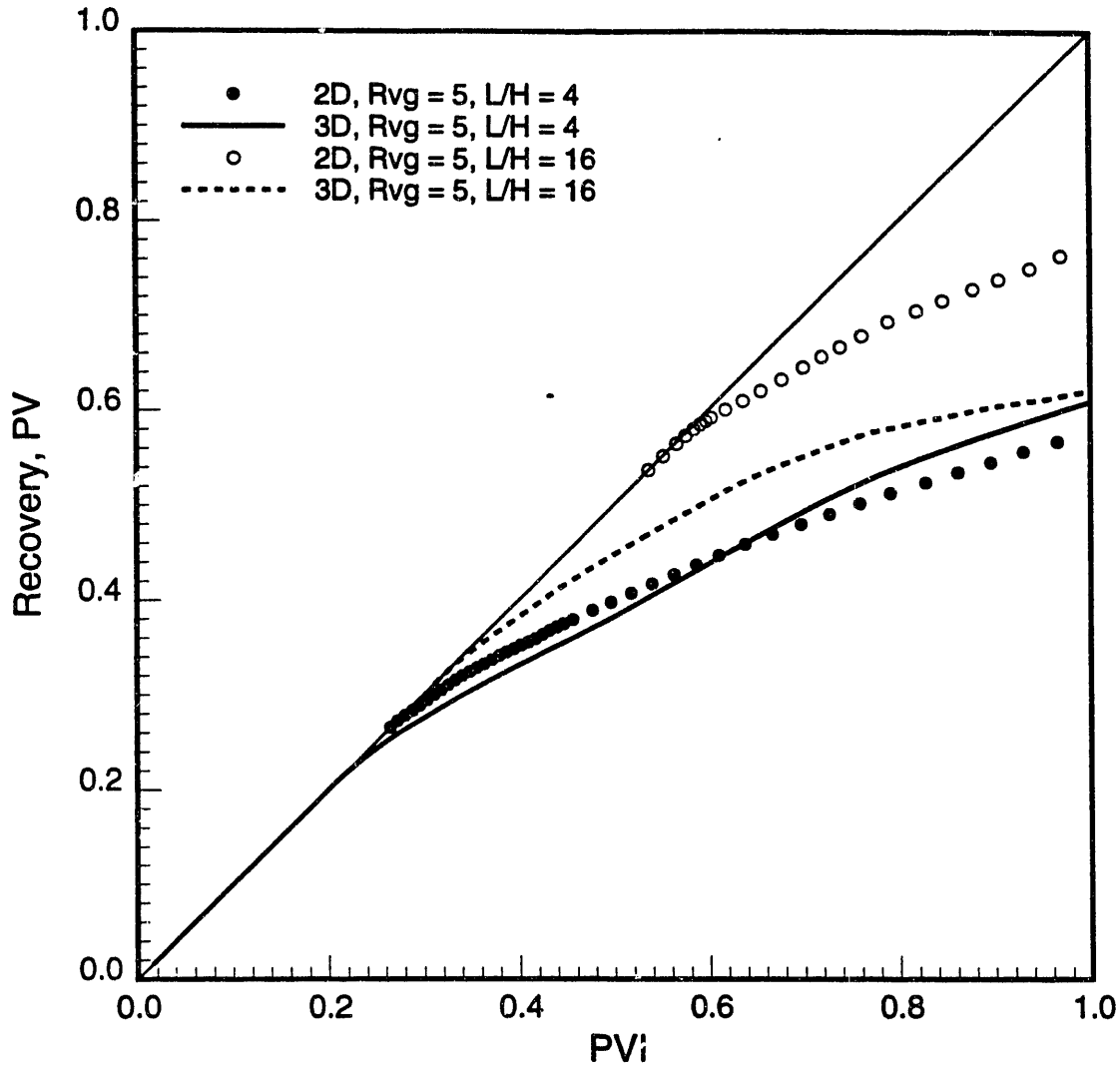

Figure 6: Comparison of calculated oil recovery for 2D and 3D simulations including gravity segregation.

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