High Resolution Prediction of Gas Injection Process Performance for Heterogeneous Reservoirs

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Abstract

This report outlines progress in the fourth quarter of the first year of the DOE project "High Resolution Prediction of Gas Injection Process Performance for Heterogeneous Reservoirs". A new approach for qualitative evaluation of the impact of numerical dispersion in compositional finite difference simulation is described. The approach, based on solutions to one-dimensional (1D) flow equations obtained by the method of characteristics (MOC), results from current research on automatic generation of analytical solutions for 1D-gas injection problems. The assessment of the effects of numerical dispersion is demonstrated in a 2D case study of a miscible flooding using multicomponent fluid descriptions. The case study demonstrates the utility of combining streamtube methods with the analytical theory of 1D-gas injection processes.

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1. Executive Summary

Compositional simulation of multicontact miscible (or near-miscible) gas injection processes is typically performed using numerical finite difference (FD) schemes. Such simulations are intrinsically affected by numerical dispersion. It has previously been demonstrated for one-dimensional (1D) displacement problems that sensitivity of a given ternary system to the presence of numerical dispersion is related to the phase equilibrium of the specific system. In this report, the analysis of the impact of numerical dispersion is extended to more realistic multicomponent fluid descriptions. Initially, a detailed analysis of grid size effects on the recovery predictions for 1D displacements of a $CH_4 - C_4 - C_{10}$ system by pure N_2 and mixtures of N_2 and CH_4 is given. The analysis, which is based on the geometrical structure of dispersion-free analytical solutions obtained by the method of characteristics (MOC), demonstrates that the sensitivity to the presence of numerical dispersion can be related to the relative orientation of the dilution line and the key tie lines making up the analytical solution in compositional space.

A predictive tool suggested from this analysis is adopted for displacement processes where pure and multicomponent injection gases are used to displace real reservoir fluids. At the minimum miscibility pressure (MMP) the quantitative variation in oil recovery predicted by coarse and fine grid numerical simulations is demonstrated to correlate well with the angle between the dilution line and a set of key lines obtained by the MOC. Thus, an algorithm previously developed for prediction of the MMP can be used to estimate the grid size sensitivity of FD simulations for a given 1-D displacement process. Hence, the new tool may be used to obtain quickly qualitative information about the sensitivity of a given system prior to any large-scale simulations.

The assessment of the impact of numerical dispersion on finite difference simulation of multicontact miscible displacement processes is demonstrated through a 2D case study. In the case study, the displacement of a multicomponent oil by separator gas and pure N_2 is simulated using two different techniques: a commercial simulator based on a finite difference formulation of the conservation equations and an existing streamtube simulator combined with new analytical one-dimensional solutions generated by the MOC.
The case study clearly demonstrates the power/potential of combining streamtubes/streamlines with the analytical theory of gas injection processes in terms of computation speed and in terms of the accuracy of the simulation result.

2. Introduction

This report presents the resent results from the research project: "High Resolution Prediction of Gas Injection Process Performance for Heterogeneous Reservoirs". The overall goal of current research project is to develop set of ultra-fast compositional tools for the prediction of field-scale miscible gas-flood performance. Because conventional FD compositional simulation is often adversely affected by effects of numerical dispersion, a key goal is to develop a simulation approach that is also much more accurate than the conventional approach. This report presents a new approach for the assessment of the impact of numerical dispersion on FD compositional simulation of miscible gas injection processes. The new approach is based on the analytical theory of gas injection processes, utilized for the automatic generation of dispersion-free 1D solutions for multicomponent flow problems.

The effects of numerical dispersion in conventional finite difference compositional simulations have been studied extensively ever since computers were first applied to prediction of reservoir performance and generation of production forecasts. The papers of Stalkup[10] and Lim *et al.*[8] are examples of such studies. This paper focuses on the apparent system specific sensitivity to numerical dispersion observed for the numerical simulations reported by Jessen[6]. Analysis of this phenomenon considers the impact of numerical dispersion on FD solutions for 1-D displacement problems in homogeneous porous media. Further, in this report we consider only the simple but commonly applied single-point upstream weighting formulation of the mass conservation equations. Numerical dispersion in this type of simulation emerges partly from truncation errors introduced by the finite difference representation of the convective term[7], and partly from the fact that FD simulations of this kind basically correspond to a sequence of interconnected mixing cells. Aris and Amundson[1] demonstrated the asymptotic equivalence of mixing cells in series and the convection-diffusion equation. In mixing cell terminology, the characteristic of numerical dispersion is that material entering one cell can be allowed to enter the next cell faster than normal flow would allow. The magnitude of the artificial dispersion is of the order $\Delta z/2$, which for reservoir scale modeling often exceeds what is physically realistic[9]. Three different formulations of the 1D displacement problem have been used in this work. Two simplified simulators assuming a low gradient in pressure compared to the overall pressure are employed. One of these further assumes that the components take up constant volume during the displacement process. The latter model is referred to as the no-volume-change (NVC) formulation. Finally the commercial simulator Eclipse 300 has been used.

3. Analysis for 4 Component Systems

Walsh and Orr[11] demonstrated, on the basis of 1-D ternary displacement problems, that the sensitivity to numerical dispersion for a given system is related to the phase behavior of the system in terms of the size and the shape of the two-phase region. The basic ideas of Walsh and Orr[11] have been combined with the intersecting key tie-line approach[12, 4] and extended to apply to miscible displacements of multicomponent systems. Consider the displacement of the quaternary system (Oil A) by pure N_2 at 305 atm and 344 K. Dindoruk[2] analyzed in detail the analytical solution to this displacement problem at a pressure well below the MMP (P < 305 atm). The geometrical structure of the displacement process is shown in Figure 1.

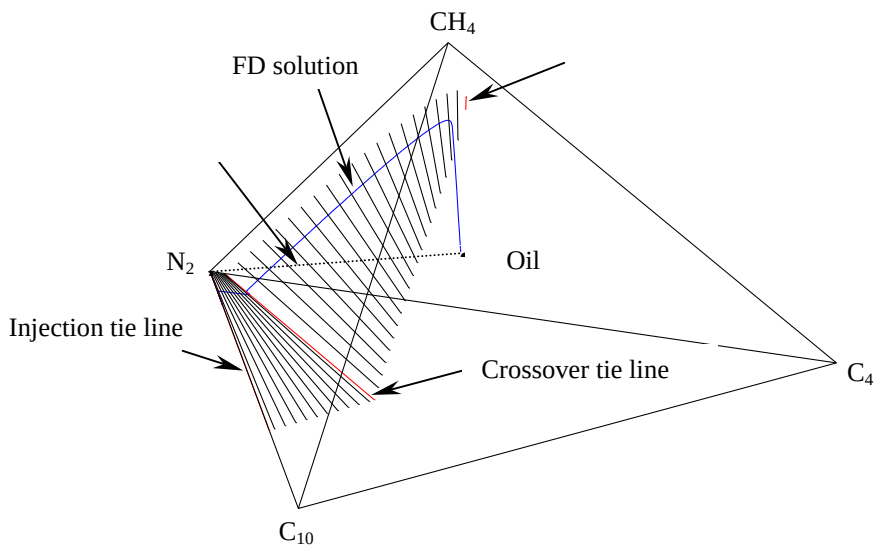

Figure 1: Displacement of Oil A by pure N_2 at 305 atm and 344 K. The FD solution was obtained using 1000 grid blocks and $\Delta z/\Delta\tau = 10$.

Figure 1 illustrates the key tie-lines predicted by analytical theory[4] along with a FD solution path obtained by use of 1000 grid blocks and $\Delta z/\Delta\tau = 10$. At the given temperature the MMP of the current system is predicted to be 309 atm. Thus, the displacement process shown in Figure 1 is nearly miscible, as can be seen from the length of the initial tie line, which is quite close to the critical locus. The mechanism controlling the development of miscibility is a pure vaporizing drive, and hence an enriched gas phase becomes locally miscible with the initial oil at the displacement front. The initial oil is located on the $CH_4 - C_4 - C_{10}$ surface of the quaternary diagram. The initial tie line is also located on this surface and the dispersion-free analytical solution (not shown) must enter the two-phase region along this tie line. The initial tie line is connected to the crossover tie line by a nontie-line rarefaction (spreading wave). In this case the crossover

tie line is located on the $N_2 - C_4 - C_{10}$ surface. A shock connects the crossover tie line to the injection tie line, which is located on the $N_2 - C_{10}$ line of the phase diagram. The recovery vs. pressure curve for this displacement problem has been generated by analytical calculations and is compared with coarse and fine grid numerical simulations in Figure 2.

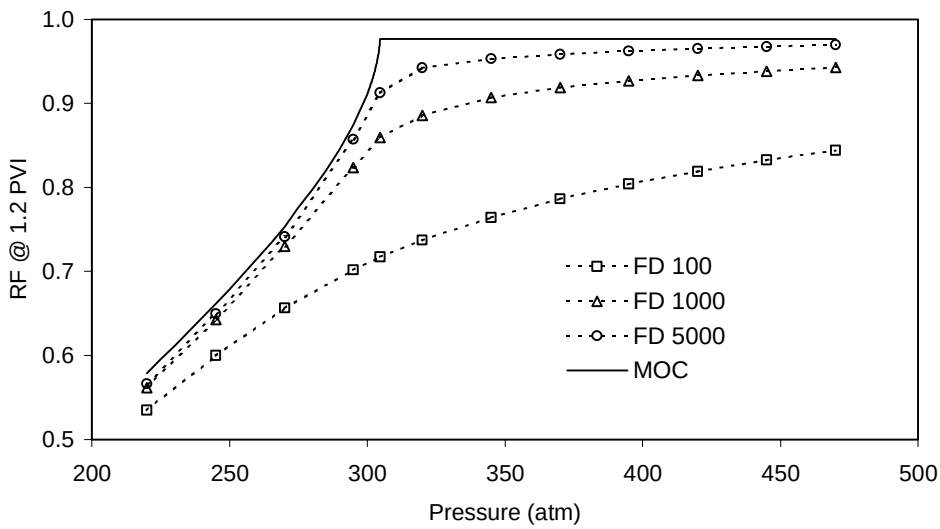

Figure 2: Comparison of recovery curves from analytical and FD simulations for the displacement of Oil A by pure N_2 at 344 K. The FD simulations were performed with 100, 1000 and 5000 grid blocks and $\Delta z/\Delta\tau = 10$.

Figure 2 clearly demonstrates that the oil recovery calculated by FD simulation of the displacement process illustrated in Figure 1 is strongly affected by numerical dispersion if coarse grid blocks are used. The geometrical structure of the displacement process (Figure 1) can be used to explain this high sensitivity to the presence numerical dispersion. At the beginning of the numerical simulation, injected N_2 is mixed with the initial oil along the dilution line connecting the two compositions (dotted line). As the oil is mixed with the injected N_2, the composition path starts to move along the dilution line until the boundary of the two-phase region is reached. Note that the mixing along the dilution line essentially corresponds to the case of no flow and pure diffusion. The orientation of the tie lines in the two-phase region forces the liquid composition of the first two-phase contact down towards the $N_2 - C_4 - C_{10}$ surface (and the injection tie line), whereas the corresponding gas phase has higher CH_4 concentration which creates mixtures closer to the initial tie line. Thus, the interaction of phase behavior and flow acts to drive the composition path of the displacement away from the dilution line. This suggests that the orientation of the dilution line with respect to the direction of the initial tie line (critical tie line) can be used as a measure of the sensitivity of the current system to the effects of dispersive mixing. To test for the existence of such a relationship, an injection gas consisting of 10% N_2 and 90% CH_4 was injected into Oil A. The structure of the displacement process is shown in Figure 3.

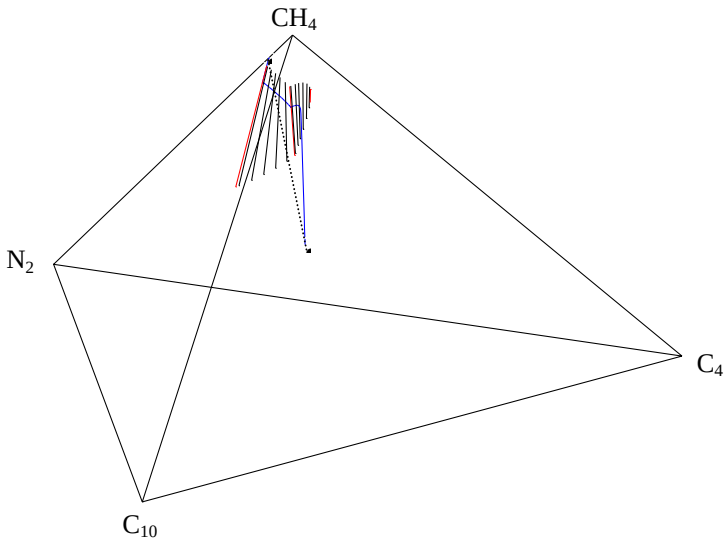

Figure 3: Displacement of Oil A by 10% N_2 and 90% CH_4 at 305 atm and 344 K. The FD solution is the result of a 1000 grid FD simulation with $\Delta z/\Delta\tau = 10$.

The injection of a CH_4-rich gas does not alter the location of the initial tie line and hence the MMP for the displacement process is identical to the MMP for injection of pure N_2. The general structure of the analytical solution also remains the same. This experiment was performed to force the dilution line to have an orientation similar to that of the initial tie line. Recovery curves for this displacement process, based on analytical calculations and FD simulations, are compared in Figure 4. In this example, the numerical simulations converge rapidly towards the analytical recovery curve as the number of grid blocks is increased. Thus, the sensitivity of this displacement process is very different from that observed for pure N_2.

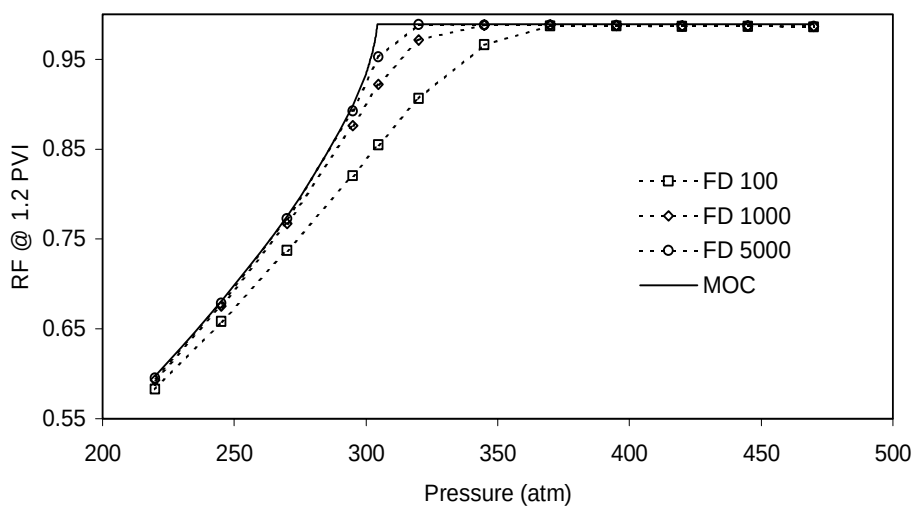

Figure 4: Comparison of recovery curves from analytical and FD simulations for the displacement of Oil A by 10% N_2 and 90% CH_4 at 344 K. The FD simulations were performed with 100, 1000 and 5000 grid blocks and $\Delta z/\Delta\tau = 10$.

A comparison of the composition paths shown in Figures 1 and 3 and the calculated recoveries shown in Figures 2 and 4 reveals that the relative orientation of the dilution line and the initial tie line (critical tie line) has a major impact on the significance of numerical dispersion in FD simulations of the investigated system

4. Multicomponent Systems

Considerations similar to those applied to the investigation of the quaternary system can be applied to multicomponent systems. The results from the previous analysis suggest that the distance between the dilution line and the critical tie line can be used as an indicator for the significance of the sensitivity to numerical dispersion for a given system. In compositional space, the points defined by the initial oil composition, the injection gas composition and the composition of the critical tie line (at P = MMP) marks up a triangle as sketched in Figure 5.

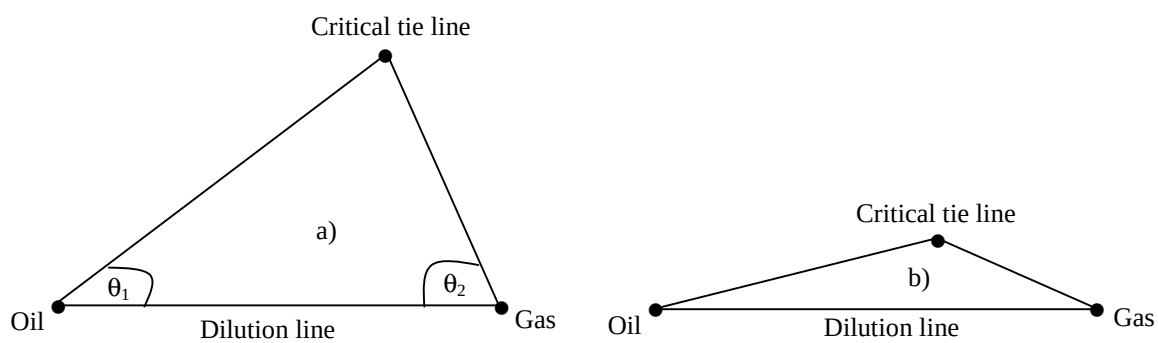

Figure 5: General triangular planes in 1D dispersion-free gas injection processes. Case a): The system is expected to be very sensitive to numerical dispersion due to the large distance from the dilution line to the critical tie line. Case b): The system is expected to be less sensitive to numerical dispersion due to the small distance from the dilution line to the critical tie line

Figure 5a is equivalent to the displacement of Oil A by pure N_2 where the critical tie line is located far away from the dilution line. In Figure 5b the distance from critical tie line to the dilution line is smaller. Hence, we expect lower sensitivity to the presence of numerical dispersion in FD simulations similar to what was found for the injection of the CH_4/N_2 mixture in Oil A. The distances between the critical tie line and the dilution line can be estimated by evaluating the angles θ_1 and θ_2. The triangles of Figure 5 are not a unique property of the four component cases studied above. For multicomponent systems one can still construct the triangle and evaluate the angles θ_1 and θ_2.

To test the use θ_1 and θ_2 for prediction of the system specific sensitivity to numerical dispersion, we next consider the displacement of the more realistic reservoir fluids B and C. The phase behavior of these fluids both represented by 15-component fluid descriptions. The reservoir temperature of case B is 387 K at which the saturation pressure of the initial oil is 249 atm. Details of the fluid description are given in Jessen[6].

Besides a light separator gas, injection of pure N_2, CH_4 and CO_2 as well as mixtures of these is considered. The second multicomponent case (Oil C) is displaced at 368 K where the saturation pressure of the initial oil composition is 251 atm. The characterization of Oil C is given in Høier[3]. The variations in recoveries after 1.2 PVI predicted by coarse and fine grid (100/5000) FD simulations were determined for the near-miscible displacement processes (P ≈ MMP). The relative variations are plotted against the maximum angle $max(\theta_1, \theta_2)$ between the critical lines and the dilution line (Fig. 5) in Figure 6.

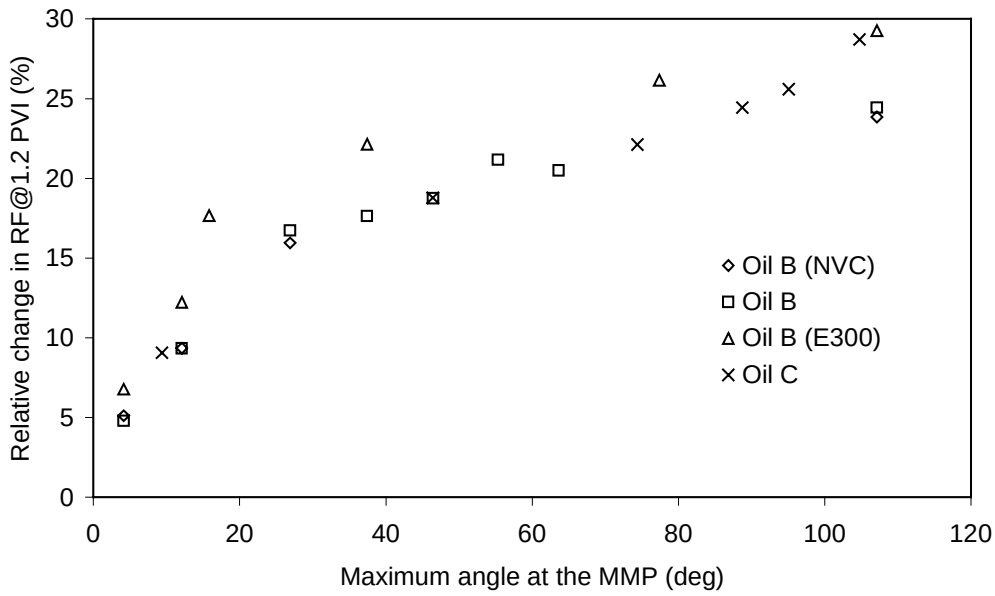

Figure 6: Sensitivity to numerical dispersion at the MMP vs. the maximum angle between the dilution line and the critical lines. The plot includes numerical simulations with and without volume change on mixing.

Some scatter is observed in Figure 6, but a relationship is evident. As the distance from the dilution line and the critical tie line (as measured by the angles θ_1 and θ_2) increases, the gas injection process becomes more sensitive to the presence of numerical dispersion. Figure 6 includes FD simulations using a simplified slimtube simulator with and without affects of volume change on mixing. In addition, results from the commercial simulator Eclipse 300 are included.

We have shown therefore that two methods can be used to obtain an indication of the sensitivity of a given system with respect to numerical dispersion. The sensitivity can be calculated directly by performing fine and coarse grid numerical simulations at the MMP and monitoring the variation of the predicted recovery. However, the computational expense of such studies can be quite significant, in particular for sensitive gas-oil systems. Alternatively, the distance from the dilution line to the critical tie line can be determined from MMP calculations by the global approach[4] where the approximate key tie lines are located in the compositional space. That approach, along with the relationship shown in Figure 6 can be used to obtain an indication of the significance of numerical effects at very low CPU cost.

5. Two-dimensional Case Study

The analysis of system specific sensitivity to the presence of numerical dispersion given in the preceding sections is based on the use of 1D-model systems. Hence, an obvious question to ask is whether the new approach can be applied to 2D and 3D problems. To examine this question we consider the displacement of the multicomponent Oil B in the 2D heterogeneous porous medium shown in Figure 7.

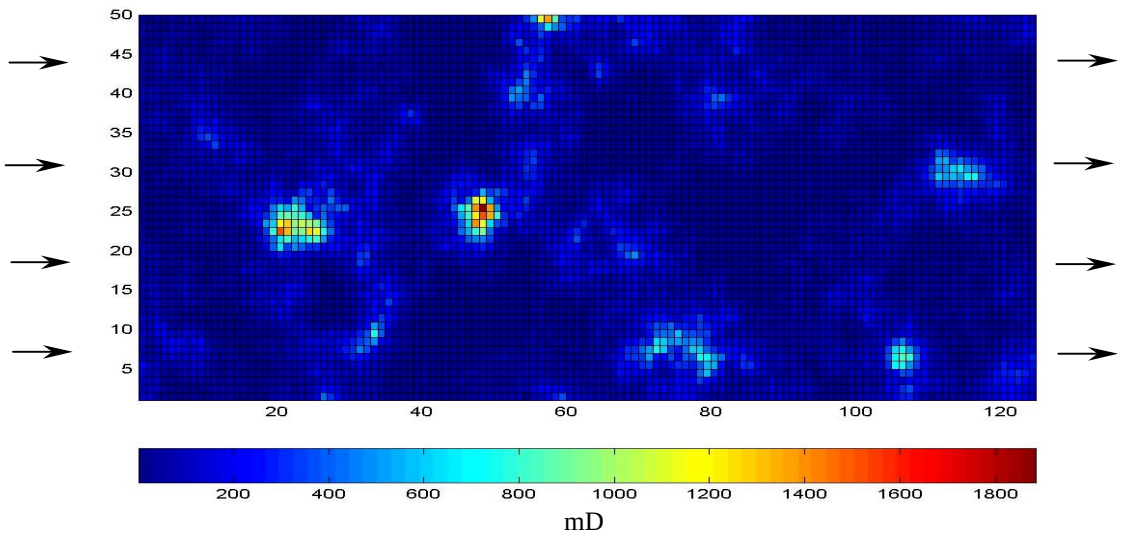

Figure 7: 2D permeability field used in case study.

To avoid any interactions between gravity effects and phase behavior dependent numerical dispersion, the displacement problem is simulated for an areal slab geometry. 125 grid blocks are used to represent the length of the slab whereas 50 grid blocks are used for the width. Gas is injected over the entire length in one end and fluid is produced at the other (Fig. 7).

5.1 Injection of a light separator gas

In the first example calculation, a light separator gas is injected for which the maximum angle predicted by the 1D approach is ~5°. According to Figure 6, only minor impact of numerical dispersion is expected (Fig. 6). The displacement problem has been simulated by two fundamentally different methods: first by using the FD based simulator Eclipse 300 and second by combining existing streamtubes methods[13] with new dispersion-free analytical 1D solutions. This selection allows us to compare a solution affected by numerical dispersion with a dispersion-free solution and quantify the difference. Secondly the CPU times needed for performing the two types of simulations can be compared. The gas is injected at the MMP (365 atm, 387K) at a constant rate. Snap shots

of the displacement process after 0.3 pore volumes injected are shown in Figure 8 for the two simulation approaches.

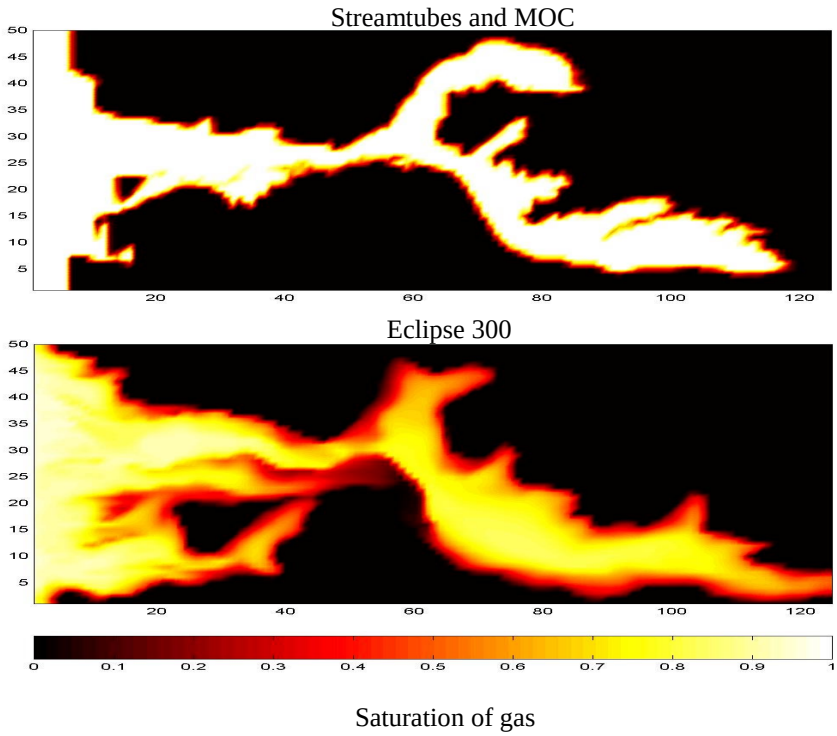

Figure 8: Displacement of Oil B by separator gas at the MMP. Gas saturation distribution of after 0.3 pore volumes injected.

Figure 8 clearly demonstrates the effects of numerical dispersion in the FD simulation. Although the swept areas are in good agreement (because the high permeability zones that dominate the flow are the same for both simulations), the saturation fronts are smeared out in the FD simulation causing a slightly early breakthrough compared to the

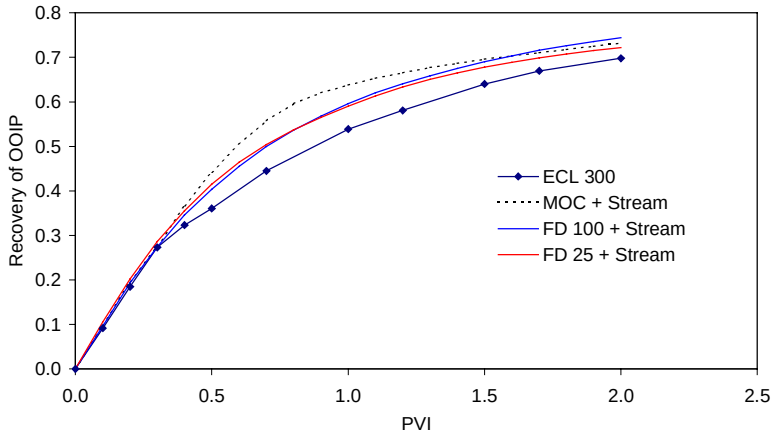

Figure 9: Cumulative oil recovery vs. PVI simulated by E300 and Streamtubes + MOC. Also included in the figure are the results of using dispersed 1D solutions in combination with streamtubes.

dispersion-free simulation. Figure 9 reports the oil recovery as a function of pore volumes injected. The recovery curves predicted by the two methods differ by a relatively small amount, and hence, the effect of numerical dispersion is relatively small, as is expected from the 1D analysis. After an earlier breakthrough, the FD simulation ends up at a lower ultimate recovery after 2.0 PVI. In order to demonstrate that numerical dispersion accounts for the difference in calculated recovery, artificial dispersion was added to the streamtube approach by using numerical 1D solutions rather than analytical solutions. In one case 100 grid blocks was used to generate the 1D solution and in another case only 5 grid blocks. As the amount of dispersion in the streamtube approach increases, better and better agreement with the E300 simulation is obtained. However, the level of numerical dispersion needed to match the E300 simulation is far beyond what is physically realistic.

The CPU times needed for the FD simulation was 33775 seconds, while the streamtube simulation required only 498 seconds, a speedup of about 67. The speedup obtained by using streamtubes in combination with analytical 1D solutions, along with the fact that the streamtube simulation is more accurate, clearly demonstrates the potential for this approach in compositional simulation.

5.2 Injection of pure N_2

In the second example, pure N_2 was used to displace Oil B. The maximum angle predicted by the 1D approach is ~100° and hence in this case we expect a more significant impact of numerical dispersion. Again N_2 is injected at the MMP (380 atm, 387 K). A snap shot of the displacement process is given in Figure 10.

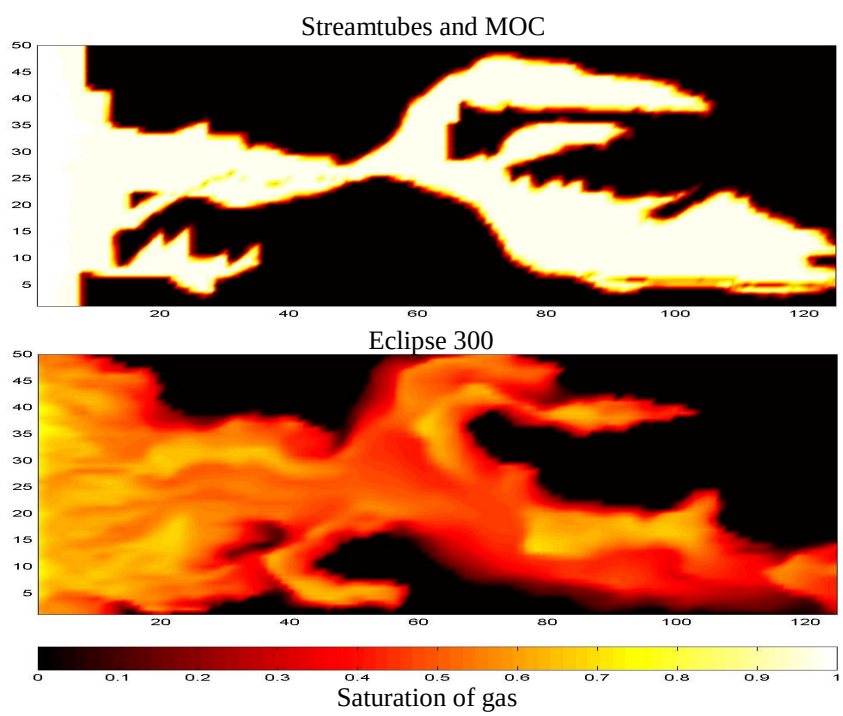

Figure 10: Displacement of Oil B by pure N_2 at the MMP. Gas saturation distribution of after 0.3 pore volumes injected.

Figure 10 shows that the disagreement between the swept areas is much larger than in the previous displacement problem. The gas saturation in the E300 simulation hardly exceeds 50%, an indication that the effects of numerical dispersion in the FD simulation are far more significant for this system. A similar conclusion is obvious from the recovery curves shown in Figure 11.

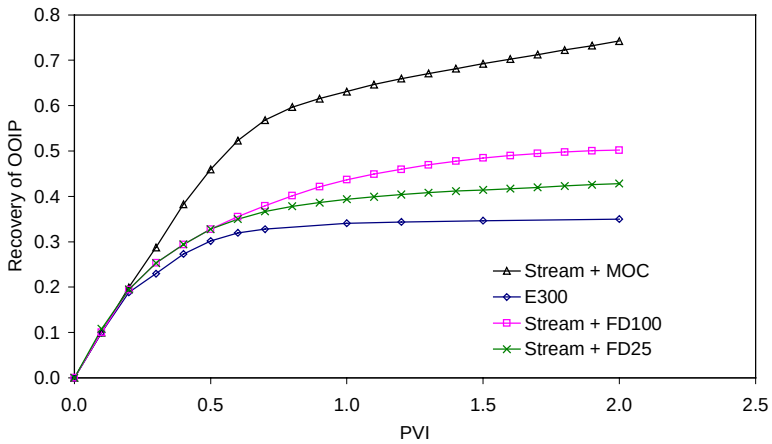

Figure 11: Cumulative oil recovery vs. pore volume of N_2 injected, simulated by E300 and Streamtubes + MOC. Additional recovery curves was generated by using dispersed 1D solutions in combination with streamtubes.

The ultimate recovery after 2.0 PVI predicted by the FD simulation (E300) is roughly 40% lower (absolute) than what is predicted by the dispersion-free approach. Again, numerical dispersion was added to the streamtube approach using 1D solutions obtained by using 100 and 25 grid blocks. Using the very coarse gridded (25) 1D solution in the streamtube approach shifts the recovery curve dramatically down towards the E300 curve. This behavior suggests that the E300 simulation is strongly affected by numerical artifacts. The level of numerical dispersion in the E300 simulation can be reduced by grid refinement. However, the CPU time needed for running such simulations will increase dramatically.

6. Conclusions

The analysis and examples given in this paper confirm the results presented by Walsh and Orr[11]. They demonstrated that the sensitivity of a given ternary system to the presence of numerical dispersion depends on details of the phase equilibrium of the specific system. The considerations of Walsh and Orr[11] have been applied for systems with more than three components. Detailed analysis of the grid size effect on the recovery predictions for the displacement of a $CH_4 - C_4 - C_{10}$ system by pure N_2 and mixtures of N_2 and CH_4 is performed. The analysis based on the geometrical structure of the true dispersion-free solutions, shows that the sensitivity to the presence of numerical dispersion can be related to the relative orientation of the dilution line and the line connecting the initial oil to the critical tie line.

The predictive tool suggested from the analysis of the quaternary system was used to study displacement processes where pure and multicomponent injection gases are used to displace real reservoir fluids. The quantitative variation in $RF_{1.2\ PVI}$ predicted at the MMP by numerical simulations proves to correlate well with the maximum angle between the dilution line and the critical lines, connecting the initial oil and the injection gas to the critical tie line. Thus, the algorithm developed for prediction of the MMP[4] can be used to indicate the grid size sensitivity of FD simulations for a given 1-D displacement process.

The similarity in grid size effects for the simplified FD simulators and E300 indicates that the new predictive tool can be used as guidance for selection of proper grid sizes when commercial simulators based on upstream weighting schemes are employed.

A 2D case study has been performed, demonstrating that the findings for the 1D-displacement processes also apply for problems of higher dimensions. Existing streamtube code has successfully been combined with new dispersion-free analytical 1D solutions for multicomponent displacement problems. Furthermore, the case study stresses the fact that extreme care must be taken in selecting a proper grid resolution if using FD based simulators for performance prediction of multicontact miscible gas injection processes. Finally, the potential for using streamtube/streamline methods in combination with the analytical theory of gas injection for simulating miscible floods is augmented by the significant possible speedup.

7. References

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