were performed using both a fully implicit and an implicit-pressure, explicit-saturation (IMPES) formulation. For the coarse grid, the implicit simulation took 14 hours while the IMPES simulation took 36 minutes. The fine-grid 3D simulation took 14 hours using the IMPES option. For ECLIPSE-VE, the fully implicit option was fastest and used 19 minutes, while the IMPES time-stepping scheme used 2 hours. MRST-VE is based on a sequential splitting approach and took 12 minutes.

Figure 3 shows CO_2 saturation in the top cells of the model at the end of injection (32 years) and end of the simulation (132 years). Overall there is a very good agreement between the solution computed with the ECLIPSE-3D simulator in a fine grid and the two VE solutions. The difference between the two ECLIPSE-3D simulations are due to numerical errors that diminish as the grid is refined in the vertical direction. In particular, the CO_2 plume simulated with the coarse grid moves slower than the one simulated with the fine grid. This observation is confirmed by Figure 4, which shows simulated CO_2 saturations in a vertical cross-section that passes though the injection point and is parallel to the x-axis. The difference in plume speed between the coarse and fine grids is caused by CO_2 moving more rapidly for higher saturation values. The large cell size of the coarse grid results in a large difference between the average of the nonlinear relative permeability functions and the relative permeability functions evaluated in the average saturation. The smaller size of the cells in the refined grid reduce this effect and the CO_2 plume expands faster. As the CO_2 plume moves away from the injection area following the top of the numerical domain, it becomes thinner and the numerical errors due to poor vertical discretization become more important. This source of error is absent in the VE models because the vertical geometry of the plume is implicitly accounted for.

Figure 4 also confirms that vertical segregation of CO_2 and brine occurs in relatively short time and that the system reaches vertical equilibrium even before the end of the injection period. Similar patterns were observed in several other cross-sections that are not shown here. If capillary forces were included, they would not change the time required to reach vertical equilibrium, but would introduce a capillary fringe. If the capillary fringe is smaller than the vertical resolution, the vertically-averaged model will still give a better description of the system than the 3D model. Introducing capillary forces in the vertically-averaged model for our homogeneous system, however introduces very little extra computational complexity. If capillary forces were included in the simulations discussed here, the thickness of the capillary fringe would be smaller than the vertical cell spacing, hence the VE models would also give a better representation of the system than the full 3D models.

4. Conclusions

We have presented results of full 3D and 2D vertical-equilibrium simulations of the migration of CO_2 in a realistic model of a site where CO_2 has been stored for more than a decade. The analysis of these results demonstrates that for the specific case of CO_2 migration in the Utsira Sand aquifer, VE models provide solutions that are more accurate. The VE model is much faster than corresponding 3D simulations that resolve the same dynamics. VE models are also more accurate than 3D models when full local segregation is achieved, because the vertical extension of the CO_2 plume is implicitly included in the model so that the VE results are independent of the vertical resolution. This is particularly important for simulations of long-term migration of CO_2, where the plume thins out as it moves farther from the injection site. The VE models have reduced dimensionality compared with full 3D models and also avoid thin cells, thereby gaining a computational advantage. In addition, VE models perform better because of the weaker coupling between the pressure and transport equations [26] which make them more suitable for sequential splitting approaches. Such splitting approaches can be troublesome in three-dimensional simulations of CO_2 migration because of the strong coupling between the pressure and saturation equations caused by gravity.

Based on the results discussed above, we recommend that more effort should go into developing more accurate and faster VE models for simulating CO_2 migration. Moreover, we anticipate that the renewed interest in vertical equilibrium models will result in the development of new simulators that would be able to represent more complex physical mechanisms that affect CO_2 migration such as capillary pressure and CO_2 dissolution into brine.

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