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Accurate coarse modeling of well-driven, high-mobility-ratio displacements in heterogeneous reservoirs

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Abstract

High mobility ratios are often encountered in improved-oil-recovery processes because the displaced oil can be much more viscous than the injected water or gas. In this work, a new two-phase upscaling approach for modeling high-mobility-ratio displacements is developed and applied. For the near-well region, a specialized upscaling procedure, which includes single-phase and two-phase upscaling components, is presented. In this upscaling, local regions around each well are considered and the coarse-scale well indices, wellblock transmissibilities, and relative permeabilities are determined such that the fine- and coarse-scale flow rates are in agreement. Away from wells, the upscaled relative permeabilities for each coarse block are computed by imposing effective flux boundary conditions, which have been shown to provide better accuracy than standard procedures. The performance of these techniques is demonstrated by considering multiple realizations of synthetic 3D models with varying correlation structures and degrees of spatial variability, as well as different fluid mobility contrasts and production scenarios (involving horizontal wells and five-spot patterns). By quantifying the upscaling errors using well-defined metrics, the contribution of each component of the overall procedure to the accuracy of the coarse models is assessed. Application of the overall upscaling methodology is shown to provide significantly more accurate coarse models than those generated using standard procedures.

Keywords: Near-well upscaling; Two-phase flow; High mobility ratio; Effective flux boundary conditions; Upscaled relative permeabilities; Reservoir simulation; Horizontal wells

1. Introduction

The field of upscaling is motivated by the need to coarsen fine-scale, geocellular descriptions into coarse-scale models suitable for fast and accurate reservoir simulations. Efficient flow calculations are essential as a typical reservoir engineering study may include numerous simulations for history matching, the investigation of different well configurations for performance prediction, and the assessment of uncertainties using multiple geostatistical realizations. Despite continual improvements in computational efficiency (e.g., parallel computing), upscaling is

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still essential. This is due in part to the fact that geological models continue to grow in size. Numerous past researchers have investigated many aspects of the upscaling problem and proposed a wide variety of upscaling methods (see reviews by Farmer, 2002; Durlofsky, 2003).

In this work, we develop and apply an upscaling technique specifically designed for high-mobility-ratio, two-phase flow processes (e.g., waterflooding, immiscible gas injection) that are driven by wells. This subject is highly pertinent to the petroleum industry for a number of reasons. Waterflooding persists as the single most used improved-oil-recovery process because water/brine is commonly and cheaply available. In addition, immiscible gas injection in some cases offers an attractive means of utilizing produced gas. The viscosity of the displaced oil is often considerably greater than that of the injected fluid, in which case the displacement proceeds at a high mobility ratio.

In the context of reservoir simulation, an accurate well model is needed to numerically relate the well to the gridblock in which it is completed (i.e., the wellblock). As a result, the coarse-scale simulation model will not provide accurate flow results unless the near-well region is upscaled appropriately (Aziz et al., 1999). In our proposed upscaling approach, the near-well and inter-well regions of the reservoir are given different treatments in accordance with the distinctly different flow regimes that prevail.

In the near-well region, the flow is radial and the pressure field does not have a constant gradient. As a result, upscaling approaches that assume a linear, constant-gradient pressure field (e.g., constant pressure–no flow boundary conditions) are not appropriate near the well. Among the approaches that do apply a constant pressure gradient, a large number provide upscaled absolute permeability, designated **k*** (see review by Renard and de Marsily, 1997). In this work, we will refer to these upscaling techniques as standard **k*** (or **k*** only) approaches. It has been established that the use of such **k*** to calculate the well indices in the coarse-scale model can lead to large inaccuracies in flow results (Mascarenhas and Durlofsky, 2000). Clearly, the proper upscaling of the near-well region requires a treatment specially designed to account for the radial nature of the flow.

One possible approach for an accurate near-well treatment is the use of local grid refinement around the well. This method may be expensive, however, as more blocks are included in the simulation and small time steps may be required due to the introduction of small blocks in the high-flow region. In the past, a variety of analytical near-well upscaling methods have been proposed (Lin, 1995; Soeriawinata et al., 1997). These methods are effective and efficient in some cases but they rely on simplifying assumptions. Thus, for highly heterogeneous reservoirs, these approaches are likely to be less effective than numerical techniques.

The first numerical near-well upscaling technique was proposed by Ding (1995). He applied a global fine-scale solution of a single-phase, steady-state, incompressible, well-driven flow problem to determine the upscaled well index (WI^*) and wellblock transmissibilities (T^{w*}). Durlofsky et al. (2000) extended the method to 3D cases involving vertical wells and employed a smaller (extended local) fine-scale domain to compute the upscaled parameters. Their near-well method performed better than standard approaches in many cases even though they used a relatively small domain for the calculation of near-well parameters. In a similar but independent work, Muggeridge et al. (2002) also extended Ding's method and considered a reduced computational domain. They found the near-well, single-phase upscaling approach to be quite effective for a variety of 2D and 3D problems involving partially penetrating and non-vertical wells. Mascarenhas and Durlofsky (2000) further extended the near-well methodology by introducing an efficient Gauss-Newton optimization procedure to force agreement between the coarse- and fine-scale flow rates. They observed a significant improvement over the standard **k*** approach in a 3D, three-phase flow problem involving a horizontal producer. Recently, Zhang et al. (2005) presented a fully global upscaling technique that calculates WI^* and transmissibilities and showed that it could provide accurate results for highly heterogeneous reservoirs.

While the single-phase upscaling techniques described above often give satisfactory results, their effectiveness deteriorates with extreme levels of coarsening (two orders of magnitude or more) and if multiphase effects are dominant, for instance in a high-mobility-ratio, two-phase displacement. In such cases, two-phase upscaling techniques may also be needed. In the context of near-well upscaling, this