Available online at www.sciencedirect.com
ScienceDirect
Journal of Petroleum Science and Engineering 59 (2007) 271 – 288
JOURNAL OF PETROLEUM SCIENCE & ENGINEERING
www.elsevier.com/locate/petrol

Vorticity-based coarse grid generation for upscaling two-phase displacements in porous media

M.A. Ashjari [a], B. Firoozabadi [a], H. Mahani [b,*], D. Khoozan [b]

[a] *Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran*
[b] *Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran*

Received 31 October 2006; received in revised form 8 March 2007; accepted 18 April 2007

Abstract

Coarse grid generation from finely gridded geological model is a main step in reservoir simulation. Coarse grid generation algorithms aim at optimizing size, number and location of the grid blocks by identifying the important geological and flow features which control flow in porous media. By optimizing coarse grid structure we can improve accuracy of the coarse scale simulation results to reproduce fine grid behavior. A number of techniques have been proposed in the literature. We present a novel coarse grid generation procedure based on vorticity preservation between fine and coarse grids. In the procedure, the coarse grid mesh tries to capture variations in both permeability and fluid velocity using a single physical quantity — "vorticity" which is extracted from single-phase flow simulation. One essential element in the procedure is that the improved coarse grid (ICG) has minimum single-phase vorticity error with respect to the fine grid vorticity. Our numerical investigations on modeling two-phase flow demonstrate that the ICG represents fine grid flow behavior very closely. In addition, our analyses show that the use of single-phase vorticity has only a minor impact on the ICG generation, and its performance is not affected by two-phase flow parameters such as mobility ratio.

Keywords: Upscaling; Vorticity; Non-uniform grid; Coarse grid generation; Porous media; Two-phase flow

1. Introduction

Advances in reservoir characterization techniques and reservoir modeling have made it possible to describe a reservoir with detailed models containing one to even several hundred million grid cells. Nevertheless, in order to represent geological variation on every fine scale (e.g. mm) we need to build a model with e.g. 10^{18} number of grid cells or finer. Using this detailed model is impractical, since the flow simulators can only handle up to one million simulation cells depending on the type, objective of simulation, and computational hardware available. Unfortunately computer hardware technology advances much slower than the detailed reservoir characterization technology. Even most advanced parallel simulators can not fill the wide gap created between fine and simulation models. Therefore, reservoir simulation must be performed on a coarse grid with average (effective) flow properties. The process of finding effective properties is called upscaling for which many different methods have been proposed. A brief description of these methods can be found in Wen and Gómez-Hernández (1996a), Renard and de Marsily (1997), Farmer (2002), and Durlofsky (2003). An important aspect of

* Corresponding author. Tel.: +98 21 6616 4581; fax: +98 21 66022853.
E-mail addresses: ashjari@mehr.sharif.edu (M.A. Ashjari), firoozabadi@sharif.edu (B. Firoozabadi), hassan_mahani@sharif.edu (H. Mahani), d_khoozan@che.sharif.edu (D. Khoozan).

0920-4105/$ - see front matter
doi:10.1016/j.petrol.2007.04.006

upscaling is assigning proper boundary condition in calculation of effective permeability. While some techniques impose local boundary conditions (e.g. no-flow), the other use global coarse grid solution to mimic real boundary condition for local calculation of upscaled properties. Among variety of upscaling techniques to calculate appropriate effective block permeability (e.g. Mascarenhas and Durlofsky, 2000; Maschio and Schiozer, 2003) is the local–global upscaling (Chen et al., 2003; Wen et al., 2006) which was shown to be much robust and accurate.

Inherently, upscaling suffers from two different type of error. Replacing a heterogeneous permeability description by equivalent block permeability has direct effect on the coarse grid model behavior which is desired to be as close as possible to the fine grid response. Homogenization error is introduced by this process. In addition, numerical dispersion is also created as a result of grid coarsening and increase in the size of numerical grid blocks. Upscaling methods aim at reducing these two errors.

It has been recognized that reducing upscaling errors are in close relation with gridding techniques (Durlofsky, 2003; Wen et al., 2003a,b). Generally, an appropriate grid has the ability to reduce both mentioned errors simultaneously. This reduces (removes) the need for using two-phase upscaling e.g. pseudoisation techniques (Chang and Mohanty, 1997; Hui and Durlofsky, 2005).

Although gridding for flow simulation is an old subject, gridding techniques for flow simulation in conjunction with upscaling are relatively recent. Gridding methods could be categorized into three main groups.

Garcia et al. (1992), for the first time, introduced a gridding procedure based on the grouping of cells of similar permeability. Through incorporating the concept of "elastic" grid they adjusted the initial uniform grids until the variance of permeability within each coarse grid block was minimized. Li et al. (1995) paid special attention to global permeability features and attempted to create a coarse grid that can preserve the variance and the spatial correlation within an entire permeability field. Many other variations of these two original methods have been investigated by several researchers (Farmer, 2002). The methods incorporate only rock permeability to generate coarse grid blocks so they are called permeability-based techniques.

Alternatively, single-phase flow, which better represents fine scale geological correlations, can be used for coarse grid generation purpose. This concept develops the second group of gridding methods known as flow-based techniques. The basic goal is to use streamlines to define the high flow paths and to introduce refinement in these areas (Durlofsky et al., 1996; Durlofsky et al., 1997; Castellini, 2001). This allows the coarse grid to capture many important features of the fine grid model.

A third group of gridding has recently been developed aiming at combining flow and permeability information in grid generation procedure. Wen and Gómez-Hernández (1996b, 1998) introduced the idea of selective iterative upscaling that uses both permeability and velocity as variable to generate coarse grid. Initially, the method constructs a coarse grid only based on permeability field, using the elastic gridding technique developed by Garcia et al. (1992), and then iteratively adjusts the grid based on flow velocity interpolated from the coarse grid solution. The main drawback of the technique is constructing a suitable initial coarse grid which depends on the applied field boundary conditions. In addition the procedure entails two steps and consequently is time consuming. More recently Mahani and Muggeridge (2005) adapted a technique which essentially combines permeability and velocity information, by incorporating a single quantity i.e. "vorticity". This resulted to a non-uniform Cartesian coarse grid with high resolution at high vorticity zones in order to preserve fine grid vorticity in the coarse grid model. The more the vorticity of fine grid is preserved in the coarse grid model, the better coarse grid performance will be achieved. This is the underlying idea used in the vorticity-based upscaling technique.

Although the validity of the concept has been shown by Mahani (2005), and Mahani and Muggeridge (2005), they did not use it quantitatively in their coarse grid generation procedure. There is no guarantee that the coarse grid generated by Mahani's algorithm is the best one which preserves fine grid vorticity. Addressing this topic, this paper attempts to quantify vorticity preservation concept. This is achieved by introducing vorticity map preservation error. As discussed, a coarse grid which minimizes the value of this error would be the improved coarse grid (ICG), among all Cartesian grids that can be constructed for a fixed upscaling level. This will be shown here through a simple test case. Numerical dispersion caused by grid coarsening and high degree of non-uniformity will not be addressed here. The capability of the optimal coarse grid generation algorithm will be illustrated through simulating immiscible two phase flow for several highly heterogeneous models from the Tenth SPE Comparative Solution Project (Christie and Blunt, 2001).

2. Concept of vorticity-based upscaling

A reservoir always consists different scales of heterogeneity from very small (mm) to very large (km). All of