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Some Results on the Accuracy of a Classical Upscaling Technique Using an Intuitive Multilevel Preprocessor for Smart Simulation

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Abstract. The progress in geology has allowed the creation of high resolution reservoir models, however hardware limitations turn multiple simulations using these models unfeasible. To overcome this problem, upscaling techniques were developed allowing fine scale information to be projected onto a coarse scale discrete domain, through homogenization of petro-physical parameters, decreasing the amount of processing and storage needed, and so turning the simulation feasible. Different upscaling techniques were developed in order to improve the tradeoff between accuracy and computational performance for different boundary conditions, so studies to identify appropriated approaches and coarsening ratios to certain types of problems are important to industry, raising up the necessity of suitable tools to perform these tests. In this context, the IMPRESS (Intuitive Multilevel Preprocessor for Smart Simulation) has been developed to simplify multilevel simulations, such as those in the family of upscaling techniques. In this article, we demonstrate an application of the IMPRESS that integrates a classical upscaling technique with a commercial petroleum reservoir simulator, the IMEX. Results are presented on the second model of the 10th SPE Comparative Solution Project (10th CSP-SPE).

Keywords: Upscaling, IMEX, IMPRESS, Reservoir, Simulation.

1 Introduction

Numerical simulation of fluid flow in porous media is an important tool to manage petroleum reservoirs, contributing to increase of oil production while minimizing associated costs. Furthermore, it aids the evaluation of the economic viability of reservoirs exploitation. It is worth mentioning that the application of these simulations is not restricted to hydrocarbons reservoirs and can be easily adapted to the management of subsurface water reservoirs, for example. These simulations require a computational domain (mesh), which is derived from a geological model of the reservoir and contains the physical properties of the rock-fluid system under study, and a flux discretization strategy for the governing equations. Among the several discretization strategies available, we highlight the Two-Point Flux Approximation (TPFA) that is known to be accurate and robust for the simulation of highly heterogeneous media on k-orthogonal grids.

Formation properties, such as porosity and permeability, typically vary over many scales, hence it is not unusual for a detailed geologic description to require from 10^7 to 10^8 grid cells [1]. Meanwhile, hardware limitations constraint the size of the models of standard reservoir simulators to 10^5 to 10^6 cells [2]. The disparity between the amount of data in geological models and the number of information that can be inserted into computational models represents a relevant problem to numerical simulation of flux in porous media. In addition, reservoir management often rely on stochastic models, which in turn require multiple simulations to perform risk and uncertainty assessment. Thus, simulations of complex models on the high-resolution geological scale are usually unfeasible.

Scale transfer methods were developed to overcome this limitations [3]. Among them, the upscaling family of methods are the standard in commercial flux simulators. These methods allow information of the fine scale mesh (high resolution computational domain) to be projected in a coarser mesh (low resolution computational domain), using some sort of homogenization, that in turn, decreases the amount of processing and storage required by the simulation.

Since fine grid geological descriptions can be expected to grow further [2], studies and tests on accuracy of scale transfer methods are extremely relevant. In this context, this paper describes the framework of IMPRESS, the Intuitive Multilevel Preprocessor for Smart Simulation, which was developed to handle the preprocessing and data structure of multi-level scale-transferring techniques. To demonstrate its features, a methodology to integrate a classical upscaling technique based on single-phase flow to a commercial flux simulator was implemented using this framework. The commercial software used here is IMEX (Implicit-Explicit Black Oil Simulator) from the *Computer Modeling Group* (CMG), which is capable of modeling primary and secondary oil recovery using bi or three-dimensional meshes [4]. The upscaling technique to be considered in this work is local and flow-based. Lastly, results are presented on the second model of 10th SPE Comparative Solution Project, considering multiple coarsening ratios.

2 Fine scale governing equations

The behavior of a single-phase flow in a porous media can be described starting from the mass conservation statement, mathematically expressed as

$$\frac{\partial}{\partial t}(\phi\rho) + \nabla \cdot (\rho\mathbf{u}) + \widetilde{m} = 0, \tag{1}$$

where ϕ is the rock porosity, ρ is the fluid density, $\widetilde{m}$ is the source/sink term and $\mathbf{u}$ is the fluid velocity. Since it can be assumed that the fluid inside the reservoir is moving slowly, Darcy's law can be applied to calculate the fluid velocity using

$$\mathbf{u} = -\frac{1}{\mu}\mathbf{k} \cdot \nabla p, \tag{2}$$

where $\mathbf{u} = (u_x, u_y, u_z)$ is the Darcy velocity, p is pressure and $\mathbf{k}$ is the absolute permeability tensor, which is defined for each grid block, considering a heterogeneous reservoir. Assuming that the tensor's principal axes and the adopted coordinate system are aligned, $\mathbf{k}$ can be mathematically expressed as

$$\mathbf{k} = \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix}. \tag{3}$$

In this development, some assumptions are implied such as Newtonian and homogeneous fluid under isothermal conditions, no chemical interactions between the fluid and the rock and no electrokinetic effects. Also, gravity and capillarity influence was neglected and the rock and fluid were considered incompressible, i.e., ρ and ϕ does not vary in space and time respectively. The resulting governing equation is stated as:

$$\nabla \cdot \left(-\frac{1}{\mu}\mathbf{k} \cdot \nabla p\right) = \widetilde{q}, \tag{4}$$

where $\widetilde{q}$ is the volumetric source/sink term, stated as $\widetilde{q} = \widetilde{m}/\rho$.

3 Upscaling techniques

In a more formal definition, upscaling is the approximation of a system of partial differential equations by another, often of the same form, with known coefficients that can be solved with fewer computing resources [5]. This allows information from the high-definition computational domain to be projected in a coarser mesh, where each of the coarse blocks are comprised by a set of fine scale volumes, as illustrated in fig. 1. This is done by using some sort of homogenization strategy on the original data in order to compute an equivalent permeability and porosity on the coarse model.

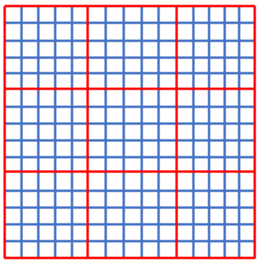

Figure 1. Illustration of a two-dimensional fine scale mesh 15x15 (blue grid) and a correspondent coarse mesh 3x3 (red grid), where each grid block is composed by a set of elements from the fine scale.

A good upscaling methodology must ensure the representativeness of the original set of informations using a smaller number of data [4]. Thus, different upscaling techniques were developed, once the ideal procedure to use on a particular problem depends on the simulation question being addressed, the production mechanism, and the level of detail that can be accommodated in the coarse model [2]. Modern upscaling techniques may vary from simple averaging of heterogeneous values within the block to sophisticated inversions [6] and the main difference among these techniques relies on how the homogenization of parameters are calculated. Although power averaging methods can be very efficient in terms of computational processing, the most robust and accurate forms to compute homogenized parameters require the solution of a fine scale flow problem [2].

The idea behind the flow-based upscaling techniques is to estimate the total flux, using a subset of the fine scale domain, in order to estimate, an equivalent permeability for the coarse mesh cell, which we will call $\mathbf{k}^*$. In order to to this, eq. (4) must be solved in the fine scale target region. If the chosen subset is restricted to the fine scale volumes contained inside a coarse scale mesh element, the upscaling is classified as local. A significant issue in any local upscaling technique is the choice of boundary conditions to be imposed in these flow problems [2]. The classical approach is to use prescribed pressure on the volumes in opposite faces from the domain (considering a structured hexahedron mesh) and no flow condition on the remaining faces, as illustrated in fig. 2. The local upscaling based in a single-phase flow with the application of constant pressure boundary condition was chosen to illustrate the use of the IMPRESS along with the standard petroleum reservoir simulator IMEX. While the procedure described above was used to compute equivalent permeability from the coarse model, the equivalent porosity was calculated from a simple volume average, once the pore volume is exactly conserved between the scales.

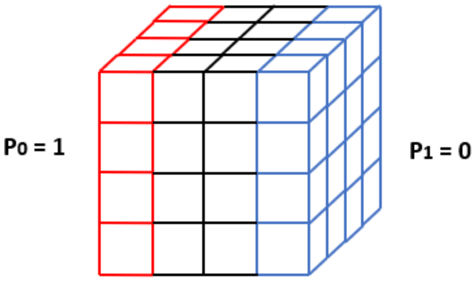

Figure 2. Boundary conditions applied to local problems. On contour faces red and blue, the pressure is prescribed as 1 and 0 respectively. On the other faces, the flow is null.

4 The Intuitive Multilevel Preprocessor for Smart Simulation - IMPRESS

IMPRESS is a preprocessor of non-structured three-dimensional meshes developed by our research group. It works in the object-oriented language Python and its objective is to offer a data structure that simplifies the development of prototypes of multiscale simulation codes. The preprocessor was created from the MOAB (Mesh Oriented Database) library, written in C++. MOAB processes mesh files and offers data structures and mesh analysis operations that form the basis for IMPRESS. In this library, each element of the mesh is represented by a handle, a 64-bit numbering. Sets of elements are stored in ranges, which are groupings of handles stored efficiently in memory.

MOAB was ported to Python through PyMOAB, an extension written in Cython, language that combines C++ and Python. This extension allowed the use of MOAB in Python codes, however it presented counterpoints such as low time performance to access and iterate over ranges and a big learning curve for beginners in programming. IMPRESS was conceived to solve these issues by adapting part of the PyMOAB and MOAB code to be accessed more efficiently by the Python code layer. In addition, it created abstractions to simplify the use of MOAB functionalities. Each element is now represented by an identifier, an integer that ranges from zero to $n - 1$, where n is the number of elements, instead of a gigantic numbering as the handle. The sets of elements started to be made available to the user in Numpy arrays, which is a Python package that offers several mathematical utilities.

The MOAB functions for analyzing the mesh and accessing elements have been adapted by IMPRESS to be made more accessible in fewer lines of code. Everything is contained in a single object that represents the mesh, whose attributes are able to return lists of elements by dimension (nodes, edges, faces and volumes), by location (internal or border), in addition to methods that make it possible to access lists of elements, adjacencies, connectivity lists, and functions that return geometric properties such as normal vector, centroid and coordinates.

To facilitate the writing of multiscale simulation codes, IMPRESS creates additional structures that represent the different mesh scales and manage the exchange of information between them. New mesh objects are created in the coarse scale, whose attributes and methods behave exactly as in the fine scale. All mesh elements are given new identifiers in the coarse scale to abstract access to the utilities of the preprocessor, according to the coarse volume to which they belong. In addition, data structures are created to organize the interfaces between the elements of the coarse scale and also to translate the identifiers between the scales.

5 Integration with commercial simulator

The methodology's goal was to integrate the local upscaling procedure to a commercial flux simulator in order to perform studies on its accuracy. The commercial flux simulator used to perform the simulations was the IMEX (Implicit-Explicit Black Oil Simulator) from CMG. Moreover, the software RESULTS, also from CMG, was used to generate the oil rate and water cut curves from the simulations.

To perform a simulation in IMEX, it is necessary to supply a dataset, containing information about the reservoir geometry, numerical parameters, physical properties of the rock-fluid system and the boundary conditions from each well. That said, the developed methodology requires a dataset from the fine scale model of the reservoir. From this file, a python module should read all physical information and initialize a mesh builder, implemented from MOAB to generate a legible mesh file to IMPRESS. The next step is to preprocess the generated mesh file, creating a multilevel mesh according to the coarsening ratio chosen by the user. Even though we call it a multilevel mesh, IMPRESS actually creates two different meshes, one of them represents the fine mesh and the other, the coarse mesh, as illustrated on fig. 3.

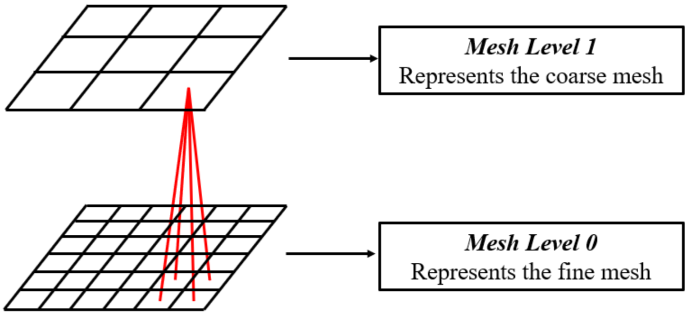

Figure 3. Visual representation of objects created by IMPRESS after preprocessing step.

Each of them have their own entities (nodes, edges, faces and volumes), but the access of these information is made through the fine mesh object, considering IMPRESS was implemented in an oriented-object environment. The fine mesh object inherits not only the information of its own entities, but also all additional levels of mesh that were created. For this reason, the fine mesh object is called *Mesh Level 0*.

A multilevel mesh is necessary because the original physical properties will be inserted in the *Mesh Level 0*, but to perform the upscaling procedure, the user must know which fine scale elements belong to each coarse scale grid block and this data is only provided by the *Mesh Level 1*, correspondent to the coarse mesh. With this information, accessing the physical properties, such as permeability and porosity, from the correct fine scale volumes to perform a local upscaling is pretty simplified. After the upscaling procedure is done and the new permeability and porosity field are available, these informations are rewritten in the IMEX dataset, with the necessary modifications in the mesh geometry and wells's positions sections. So the upscaled model is ready to be simulated in IMEX.

It is worth mentioning that the data structure that interprets and rewrites the IMEX's dataset does not belong to IMPRESS, but it was pretty simple to be developed, since our preprocessor was created to provide flexibility and extensibility. That said, the adaptation of this data structure can easily allow the integration of IMPRESS to other commercial simulators.

6 Results

Preliminary results were obtained in the second model from the 10th SPE Comparative Solution Problem. The problem consists in a three-dimensional uniform mesh with 60x220x85 elements (1,122,000 cells) containing two different geological formations: the Tabert (the first 35 layers from the reservoir) and the Upper Ness (the last 50 layers). Both formations present high heterogeneity, although they present different levels of compaction, as can be seen in fig. 4.

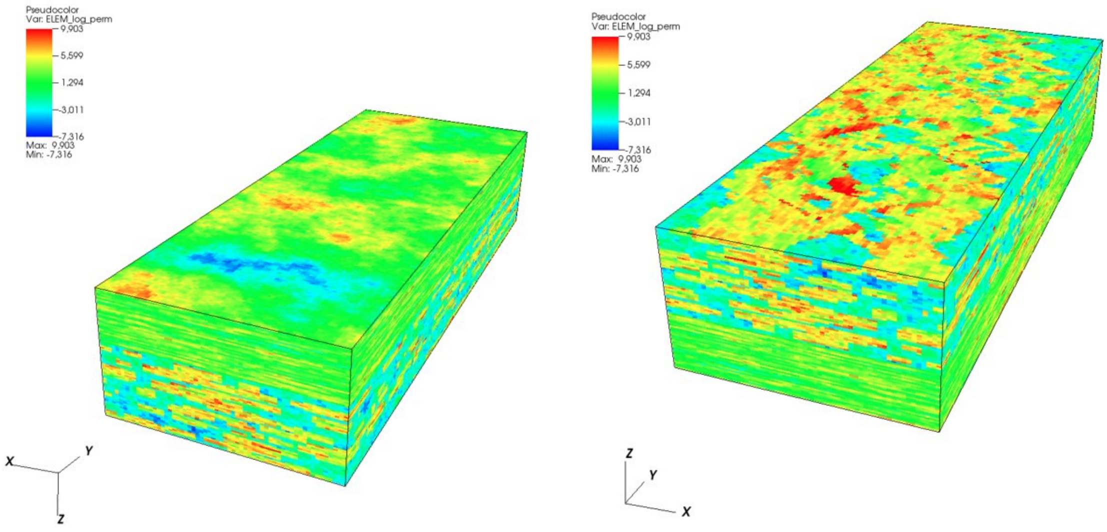

Figure 4. Field log permeability with Tabert formation in focus to the left and Upper Ness formation in focus to the right.

The configuration of this reservoir is an inverted five-spot scheme with water injection, so the injector well is positioned in the center of the domain and the four producers are in the corners. Bottom hole pressures are prescribed for all wells, maximum rate of water is determined for the injector and maximum rate of oil for the producers. Although the problem has a multiphase formulation essentially, some references justify that a single-phase upscaling can many times be sufficient to provide a good homogenization parameters (see [2] and [5]). In addition to the reference solution, obtained with the simulation of the fine mesh, other three upscaled models were analyzed. The curves of total oil rate production and water cut are presented in fig. 5, in which just reasonable results were obtained for the different coarsening ratios analysed. The coarse mesh 15x55x17 (i.e. coarsening ratio of 4x4x5 in each of directions) gave slightly better results. In fig. 6, we present the oil rate for each one of the four producers. Apart from producer 1, the coarse model 15x55x17 gave better results again.

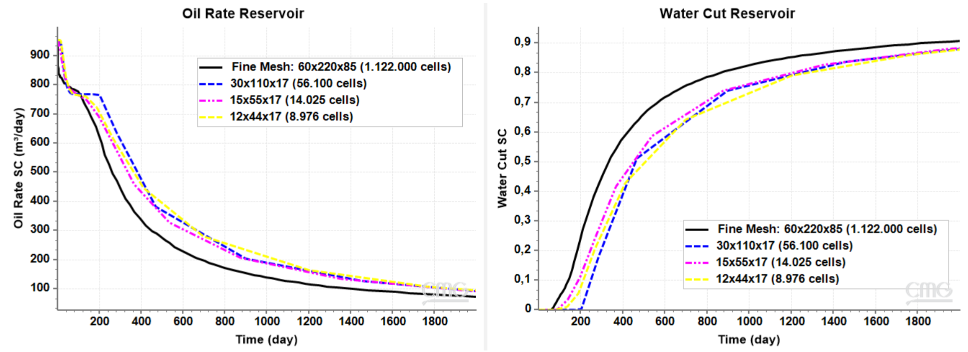

Figure 5. Total oil rate production to the left and total water cut to the right.

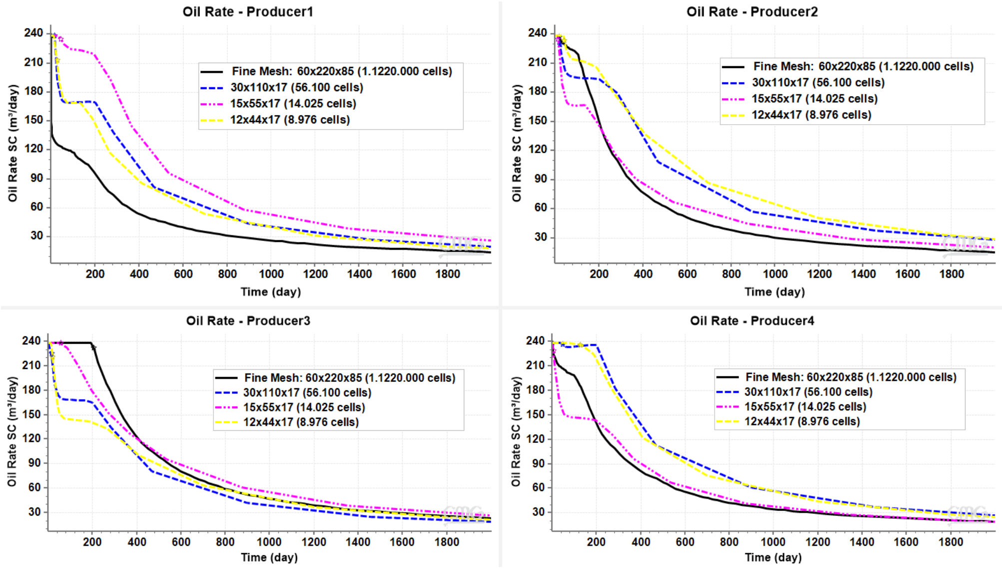

Figure 6. Oil rate for each producer well.

A possible source of error identified could be the change in the wells position caused by the upscaling of the model, as illustrated in fig. 7. It can be seen that the coarsening of the element from the corner of the reservoir leads to a geometric displacement of the producers, since IMEX considers the well positioned in the center of the cell based on the configuration provided by the dataset.

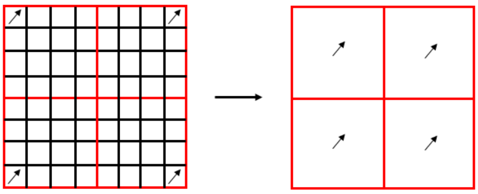

Figure 7. Displacement of wells due to upscaling.

The adoption of different coarsening rations and of non-uniform meshes, in which the wells surrounding regions are kept on fine level, are under investigation. Also, alternative extended local and global local schemes, with alternative subproblems boundary conditions, and the use of multiscale method to perform numerical upscalling are under investigation in our research group, using the framework provided by the IMPRESS, which has proved to be a flexible tool enabling rapid prototype of multiscale and upscale methodologies.

7 Conclusion

By using the IMPRESS framework, the simulation of different coarsening ratios was simplified allowing the quick evaluation of quality of results using the integration methodology with softwares IMEX and RESULTS. From the obtained partial results, we can conclude that compared to the fine mesh solution, all the upscaled methods presented reasonable global results, although the oil rate production for each well showed relevant differences from the reference solution.

Lastly, the decrease of processing time with the upscaled models illustrated in Table 1 can certify the computational gain with the application of transfer scale methods and especially, upscaling techniques. That said, development frameworks such as IMPRESS are essential to deepen investigations on these methodologies. Currently, IMPRESS is maintained in a GitHub repository in https://github.com/padmec-reservoir/impress. Analysis and improvements are being performed on its efficiency and we expect that a deeper study about it can be published in the future.

Table 1. Model's processing time

Model	CPU Time (s)
60x220x85	55,567
30x110x17	233
15x55x17	24
12x44x17	13

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