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Quad-Tree decomposition method for areal upscaling of heterogeneous reservoirs: Application to arbitrary shaped reservoirs

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HIGHLIGHTS

- Quad-Tree decomposition method was employed for upscaling of 2D geological models of arbitrary shaped reservoirs.
- Two challenging porous media including areal-layered and fractured were used.
- Two-phase flow simulation was implemented in irregular-shaped reservoirs.
- Two-phase flow simulation was implemented using unstructured computational gridblocks.
- The proposed method can make a significant computation speedup while maintaining the same accuracy as the fine grid.

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ABSTRACT

In this paper, Quad-Tree decomposition method is applied for areal upscaling of irregular shaped petroleum reservoirs. Quad-Tree decomposition is a recursive data structuring technique which generates an upscaled model with non-uniform (unstructured) gridblocks. This type of coarsening reduces the number of gridblocks, but preserves the main heterogeneity features of the original fine model. Because of the quadruplet nature of the Quad-Tree decomposition, this method cannot be used for upscaling of irregular-shaped models, directly. In this study, by circumscribing a square to the irregular-shaped reservoirs, a temporary model is obtained which can be upscaled by Quad-Tree decomposition. After upscaling, the extra gridblocks outside of the real reservoir are removed to give the final upscaled model. The proposed algorithm is used for simulation of oil and water two-phase flow in two different case studies. The simulation results demonstrate that the resulted upscaled model can give accurate results compared to the original fine model, but is 13.5 times faster than the original fine model.

1. Introduction

Undoubtedly numerical simulation of fluids flow in heterogeneous subsurface porous media is of great importance for many scientific fields [1,2]. One such field in which numerical flow simulation plays an important role is petroleum engineering. Nowadays one of the most useful tools for reservoir engineers is reservoir simulation [3]. The elementary data which are needed in the simulation of a reservoir is the spatial variation of petrophysical properties of that reservoir [4,5] which are commonly built with geological and geostatistical tools. Recent advances in geological and geostatistical techniques allow these geological models to be very fine or in other words, to have a large number of gridblocks to describe complex geological features [3,6–9]. However, these too fine and detailed geological models cannot be applied directly in reservoir simulation specially for multi-phase flow mainly due to computation time and memory constraints [7,9–12]. A natural and common way to overcome this problem is to coarsen these too detailed geological models to a coarse model with a smaller number of gridblocks in which simulation of flow can be done in a reasonable amount of computation time [7,13–15]. This process is referred to as upscaling. The key point in upscaling is that the upscaled model must mimic the dynamic performance (response) of the original fine model while preserving its significant geological features as much as possible [13,14,16–18].

Essentially the upscaling process consists of two distinct steps [19–21]. In the first step neighboring geological gridblocks such that have similar values of a desired parameter are merged to construct coarse gridblocks. This step is referred to as upgridding or homogenization. The desired parameter can be a pure geometrical

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Nomenclature

A	area of the gridblock (m^2)
B_c	oil formation volume factor (m^3/std m^3)
B_w	water formation volume factor (m^3/std m^3)
c_o	oil compressibility factor (Pa^{-1})
c_r	rock compressibility factor (Pa^{-1})
c_t	total compressibility factor (Pa^{-1})
c_w	water compressibility factor (Pa^{-1})
E	east neighbor gridblock
EN	east–north neighbor gridblock
ES	east–south neighbor gridblock
k	absolute permeability (m^2)
$\bar{k}$	effective permeability (m^2)
$\bar{\bar{k}}$	permeability tensor (m^2)
k_{ro}	oil relative permeability (dimensionless)
k_{rw}	water relative permeability (dimensionless)
$(k_{ro}/\mu_o)_e$	oil mobility in boundary between gridblocks P and E (Pa^{-1} s^{-1})
$(k_{ro}/\mu_o)_{en}$	oil mobility in boundary between gridblocks P and EN (Pa^{-1} s^{-1})
$k_{xx,E}$	gridblock E absolute permeability in x-direction (m^2)
$k_{xx,EN}$	gridblock EN absolute permeability in x-direction (m^2)
$k_{xx,ES}$	gridblock ES absolute permeability in x-direction (m^2)
$k_{xx,P}$	gridblock P absolute permeability in x-direction (m^2)
l	length of gridblock (m)
$\bar{n}$	outward normal vector (dimensionless)
P	gridblock P
P_{cow}	capillary pressure (Pa)
P_o	oil pressure (Pa)
$P_{o,E}$	oil pressure in gridblock E (Pa)
$P_{o,EN}$	oil pressure in gridblock EN (Pa)
$P_{o,ES}$	oil pressure in gridblock ES (Pa)
$P_{o,P}$	oil pressure in gridblock P (Pa)
P_w	water pressure (Pa)
P_o^{n+1}	oil pressure in time t_{n+1} (Pa)
P_o^n	oil pressure in time t_n (Pa)
$Q_{o,SC}$	oil flow rate at standard conditions (m^3/s)
$Q_{w,SC}$	water flow rate at standard conditions (m^3/s)
S_o	oil saturation (dimensionless)
S_w	water saturation (dimensionless)
S_w^{n+1}	water saturation in time t_{n+1} (dimensionless)
S_w^n	water saturation in time t_n (dimensionless)
t	time (s)
t_{n+1}	time in current step (s)
t_n	time in previous step (s)
Δt	time step (s)
λ_o	oil mobility (Pa^{-1} s^{-1})
$\lambda_{o,boundary}$	oil mobility in boundary (Pa^{-1} s^{-1})
$\lambda_{o,down}$	oil mobility in downstream gridblock (Pa^{-1} s^{-1})
$\lambda_{o,up}$	oil mobility in upstream gridblock (Pa^{-1} s^{-1})
$\lambda_{o,up-1}$	oil mobility in upside gridblock of upstream gridblock (Pa^{-1} s^{-1})
μ_o	oil viscosity (Pa s)
μ_w	water viscosity (Pa s)
φ	porosity (dimensionless)
ψ	mobility limiter (dimensionless)

parameter such as absolute permeability, a flow behavior indicator parameter such as fluid velocity or a combination of them. Regardless of the type of the desired parameter, the outcome of this step is a model with coarse computational gridblocks such that its number of gridblocks is considerably less than the original fine model. In the second step the effective values of the spatially distributed parameters (e.g. permeability and porosity) in each coarse gridblock built in the first step is calculated. This step is called property reassignment [19–21].

A wide variety of upscaling methods have been proposed in the literature that can be classified based on several ways. Based on the types of the upscaled parameters, upscaling techniques can be classified as single phase parameter upscaling or multi-phase parameter upscaling [22–24]. For single-phase flow of a fluid in a porous medium, only two parameters must be upscaled: absolute permeability and porosity [22–24]. Upscaling of porosity due to its scalar and static nature is easy and can be done by volume weighted arithmetic average [20]. However, permeability is a dynamic and direction dependent property and its upscaling is more challenging than the simple averaging methods [8]. For multiphase flow, other saturation-dependent flow properties i.e. relative permeability and capillary pressure can be upscaled [24]. There are several methods for upscaling of relative permeability. However, relative permeability upscaling often requires multiphase flow simulation and due to computation time and memory constraints is too expensive [25]. Moreover the resulting upscaled relative permeability function depends on production scenario e.g., well configuration, boundary conditions and flow direction and if the current production scenario is changed, the upscaled relative permeability functions may not be applicable [18,25]. Some researchers have shown that if upscaling of absolute permeability is performed well, and overall degree of coarsening is not severe (e.g., proportion of the upscaled model size to original fine model size must not be less than 0.01), it is not necessary to upscale relative permeability and original fine model relative permeability curves can be used for flow simulations in coarse model [3–5,23]. In this study because of these reasons, original fine model relative permeability and capillary pressure functions without any change are used for simulation of flow in upscaled models and only upscaling of absolute permeability is focused on.

In terms of the structure of the constructed coarse gridblocks, these techniques can be classified into structured and unstructured [9,25–27]. In structured approaches, a pre-defined number of gridblocks are combined to build a coarse gridblock. In these methods, the coarse gridblocks are equal-sized. In unstructured methods, at different regions, based on a predefined homogeneity criterion (e.g. permeability or fluid velocity variation), different number of gridblocks are combined to build a coarse gridblock and so the created coarse gridblocks have different sizes. For example, if homogeneity criterion is assumed to be permeability variation, it is obvious that unstructured methods can achieve the same representation of geological features such as channels, non-permeable zones, and reservoir boundaries by very fewer gridblocks than would be needed if structured methods are used [9–11]. Moreover unstructured methods can capture dynamic performance of the model better compared to structured methods [10,25–27]. Another advantage of unstructured methods is that they can reduce the number of gridblocks more efficiently and so speed up the computations. Due to the above reasons, unstructured methods have caught more attention in simulation of flow through porous media. However one disadvantage of unstructured methods is that they complicate the flow simulation computations [25]. Moreover they add some numerical dispersion error due to non-uniformity because the truncation error produced by unstructured gridblocks is more than the structured gridblocks [2,10,27]. Based on the flow dependency, these techniques can be classified as flow-based, geometrical-based