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3-Dimensional Wells and Tunnels for Finite Element Grids

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ABSTRACT

Modeling fluid, vapor, and air injection and extraction from wells poses a number of problems. The length scale of well bores is centimeters, the region of high pressure gradient may be tens of meters and the reservoir may be tens of kilometers. Furthermore, accurate representation of the path of a deviated well can be difficult. Incorporating the physics of injection and extraction can be made easier and more accurate with automated grid generation tools that incorporate wells as part of a background mesh that represents the reservoir.

GEOMESH is a modeling tool developed for automating finite element grid generation. This tool maintains the geometric integrity of the geologic framework and produces optimal (Delaunay) tetrahedral grids. GEOMESH creates a 3D well as hexagonal segments formed along the path of the well. This well structure is tetrahedralized into a Delaunay mesh and then embedded into a background mesh. The well structure can be radially or vertically refined and each well layer is assigned a material property or can take on the material properties of the surrounding stratigraphy. The resulting embedded well can then be used by unstructured finite element models for gas and fluid flow in the vicinity of wells or tunnels.

This 3D well representation allows the study of the free-surface of the well and surrounding stratigraphy. It reduces possible grid orientation effects, and allows better correlation between well sample data and the geologic model. The well grids also allow improved visualization for well and tunnel model analysis. 3D observation of the grids helps qualitative interpretation and can reveal features not apparent in fewer dimensions.

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INTRODUCTION

Subsurface flow and transport modeling is important in solving environmental and gas and oil problems involving complicated physics, chemistry, and multiphase flow phenomena. An important phase of the modeling process is grid generation. If not created carefully, grid effects can occur that result in inaccurate solutions. See Gable et al. [1] Therefore the grids used for the solution of these problems must satisfy certain criteria. From the original geologic data a grid is constructed incorporating structure, stratigraphy, material boundaries and material properties. The grid should have a point distribution and connectivity at the resolution and optimization required for computations while preserving the interfaces and geometry of the original data.

Wells represent an important boundary condition in reservoir simulations. Rapid changes and large pressure, temperature, saturation, and composition gradients occur in near-well regions. As shown by Palagi [2], the flow around wells affects the overall pressure distribution in the reservoir. Therefore, the grid geometry should be selected such that the solution has the required accuracy around wells.

Studies on grid effects for reservoir and well simulations have included many grid methods. Some of the more successful include Cartesian grids as shown by Heinemann [3] and Quandalle [4]. These grids had restricted choice for well locations and problems in following the natural flow geometry around the wells, which led to errors in the fine-to-coarse grid boundary [5]. Grids using orthogonal curvilinear systems for wells have been demonstrated [5] and are appropriate for the flow patterns of the wells. However, computational problems arise if the coordinate system is not strictly orthogonal. Pedrosa and Aziz [6] obtained a good match to numerical solutions by using a irregular Hybrid-Cartesian grid with refinement in the well region. The advantage of this hybrid grid is its flexibility, it can be refined, smoothed, and grid points can be chosen freely. CVFE (Control Volume Finite Element) grids have been used because they are flexible and can be refined so that discretization errors do not occur at the fine-to-coarse boundaries around the wells. More recently, Fung [7] combined the advantages of CVFE grids with cylindrical refinement around wells. This method improved on the Hybrid-Cartesian grid which limited the location of wells to the center of the grid cells.

This work will show a method of creating 3D well grids that not only retain features found to be successful in previous studies, but allows wells to automatically be generated along any chosen well path. The grids are designed to reduce grid effects and provide a good correlation between the input geometry and the final geologic model. They are irregular, flexible, and can be refined as needed. We are using these grids and results from previous studies to study how best to represent grids for near and far field reservoir simulations containing wells.

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OBJECTIVES

As demonstrated by previous studies, the accurate and efficient simulation of complex reservoirs depends on proper grid selection. The process of grid design should be flexible, should represent complex geometries, and should allow additional points to be concentrated near well locations. Unstructured grids can do these things [8]. Control of local grid refinement is necessary for accurate resolution. This enhances the grid quality by resolving steep gradients and eliminating dispersion errors. The size and location of wells should be chosen freely, the grids should follow the natural flow geometry around the wells, and the fine-to-coarse boundary should be smooth [2, 7, 9]. The grids must satisfy computation criteria for finite element computations including the validation of Delaunay triangulation and minimization of element aspect ratios to reduce sensitivity to grid orientation [7, 10]. Therefore, for grid generation representing reservoirs and their wells we have the following objectives:

1. Automatically generate unstructured 3D grids of wells and reservoirs that maintain the integrity of the original input geometry.
2. The grids must be Delaunay.
3. Coupling coefficients of the grids must be positive to insure flux calculations do not have negative transmissibility.
4. Reconnection to satisfy computation criteria must retain the material interfaces of the original geometry.
5. The design of the well grids should be flexible and should include local refinement and smoothing capabilities.
6. The grids should be able to represent any well geometry, vertical or deviated.
7. The ability to add wells to a reservoir grid at any location.
8. Verify the minimization of grid effects on solutions to physics process models.

AUTOMATED GRID GENERATION

X3D is an automatic grid generator developed at Los Alamos National Laboratory which allows the flexible and consistent design of computational grids [11]. Output is prepared which is usable by finite element, finite volume, and integrated finite difference methods. The final grids are constrained Delaunay, coupling coefficients are positive [12], and all material interfaces are preserved. Grids can be constructed of triangles or tetrahedra. GEOMESH is a software project that uses X3D to meet needs specific to geologic and geo-engineering applications [1, 13, 14]. GEOMESH software provides flexibility and consistency enabling grids to represent major reservoir features.

Along with automation and grid integrity, X3D provides GEOMESH with various grid functions that can be used interchangeably. The most important grid capabilities used for

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these studies are refinement and reconnection. Three methods of refinement are available; edge, face, and volume. The area of refinement is selected by a bounding box method, by selecting material types, material interfaces, element aspect ratio, field value or gradient, or any other function the user wishes to define. The final grid is reconnected such that material interfaces are preserved and the grid is Delaunay with positive coupling coefficients.

By using GEOMESH software to generate the reservoir grids, we achieve the first five of our eight objectives. The process of generating grids is automated, and the integrity of the original geometry is maintained. The grids are computationally robust and material interfaces are retained. The grids are flexible unstructured finite element that can be refined globally or locally.

VERTICAL WELLS for NEAR-WELL STUDIES

As found in previous reservoir studies, the grid area most important to construct accurately are immediately surrounding the wells. So we begin by constructing a grid for a 3D vertical well, which we can then analyze by solving a time dependent heat conduction problem.

The well and reservoir for this problem is a 3D version of a 2D radially symmetric problem used in verification studies [15, 16] for FEHM, a finite element heat and mass transport code for saturated and unsaturated porous media [17]. The FEHM 2D well was successfully compared to an analytical solution developed by Ramey [18] that predicts thermal drawdown in a wellbore. The wellbore test consisted of simulating fluid injection into the wellbore with the initial temperature distribution in the medium given by a linear geothermal gradient.

Our grid is a 3D version of the 2D FEHM verification well. The well is 2000 m deep and has a radius of 0.1m. It is embedded in the center of a cylindrical reservoir that has a 50m radius and is the same depth as the well. For these problems, the reservoir is of a single material. The entire grid is vertically refined into 20 segments of 100m length. The radial grid distances from the center are 0.20, 0.54, 1.14, 2.20, 4.0, 7.25, 12.89, 22.75, and 40.0 meters. Figure 1. shows the top view of the grid, showing the radial refinement as a gradual transition from very small faces at the center to large at the reservoir edge.

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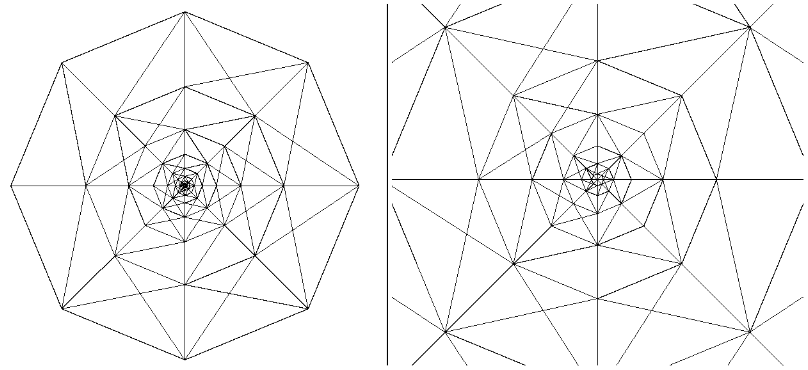

FIGURE 1. 3D grid for wellbore simulation. The view on the left shows the entire grid from the top. The right side shows a close up of the well and surrounding stratigraphy.

As explored in earlier studies, we altered the well and reservoir grid with various refinement methods and then ran the wellbore problem on the new grid. These methods included refinement radially outward from the center, a radial refinement that increased the number of radii, and refinement in the direction of elevation. Figure 2. shows some of the different grids used for the simulations. As found in earlier studies [2,6], as long as the grid is refined in the well area, and large aspect ratios are avoided at the near to far boundaries, the method of refinement for these cases does not change the solution. Figure 3. shows the comparison between solutions on the different grids.

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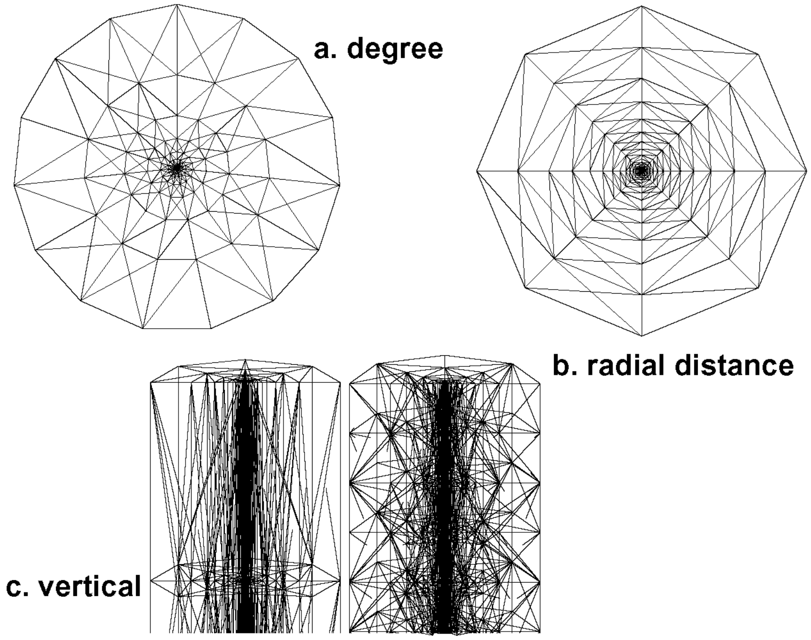

FIGURE 2. The well structure and the surrounding stratigraphy can be refined with various methods. These images show 3 methods used in testing various well structures. a. by degree - increasing the number of radii, b. by adjusting radial distances outward from the well's center and c. vertically along the well's length.

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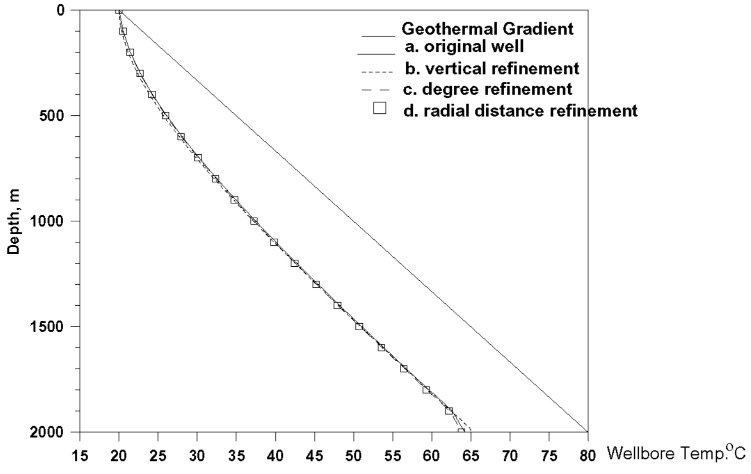

FIGURE 3. Comparison of FEHM solutions with different refinement methods.

VERTICAL WELLS for RESERVOIR STUDIES

For inclusion in a large reservoir, the previous methods are used to create the well and the near-well grid. If the reservoir grid is too coarse for the well structure, the reservoir can be refined in the vicinity of the well before the well is embedded. Figure 4. shows the vertical well from the 3D FEHM verification problem embedded in a block grid.

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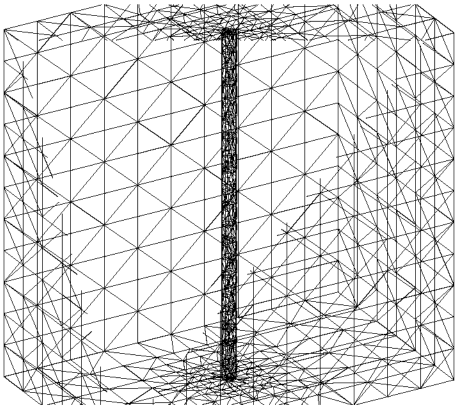
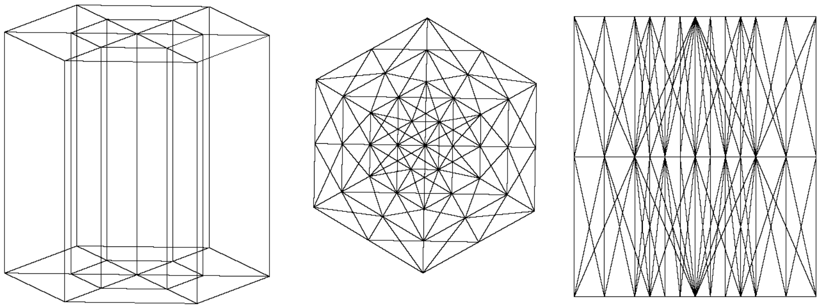


FIGURE 4. Vertical well from FEHM problem embedded in block reservoir showing refinement in locale of well grid.

DEVIATED WELLS

The vertical wells so far were generated using X3D, using commands that generate cylindrical grids. This works well for exploring vertical wells, but not wells and tunnels that are deviated and follow an arbitrary path in three dimensions. We use a GEOMESH routine called WELLMESH to create a 3D well as connected hexagonal segments formed along a given path. This well structure can be automatically refined vertically or radially during its construction. The grid is then tetrahedralized into a Delaunay grid and reconnected to ensure an accurate computational grid. Figure 6. shows this grid structure.



hexahedral well

final well - top view

final well - side view

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FIGURE 5. Deviated well structure. The figure on the left shows the hexagonal well structure with no vertical refinement and radially separated into 2 sections. The figures to the right are the same grid after it has been tetrahedralized and reconnected - top and side views.

With this well structure we can create wells along a deviated or vertical path, refine the reservoir and/or the well, then embed the well in a reservoir. From well grids for near-well studies, to expansive geologies, these wells can be used to provide grids for reservoir modeling. With this tool we will continue computations on various well and reservoir representations. This will allow us to better understand grids that give the optimal solution for a particular reservoir problem.

CONCLUSIONS

The study of near and far field effects in reservoirs present special problems in the generation of computational grids. The approach presented here offers a flexible and automated approach towards creating grids for studying simulations of wells in a reservoir. The grids are Delaunay and coupling coefficients are positive, yet the material interfaces and the shape of the input geometry are maintained. The wells can be vertical or deviated, with different methods of refinement available. Further work will study the effects of particular representations of the grid near the well bore and their effects on rest of the reservoir.

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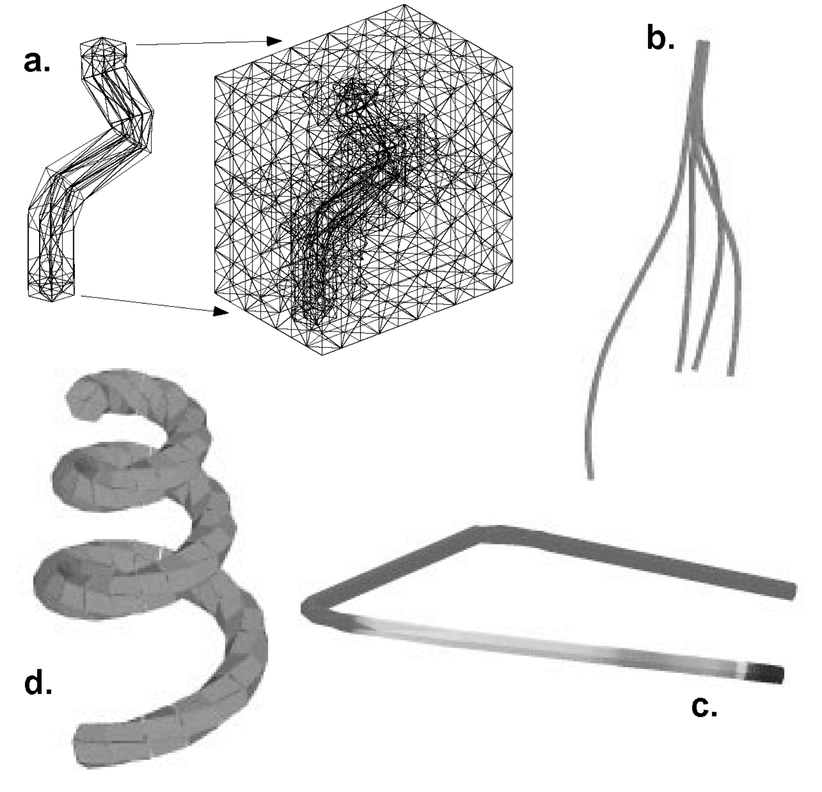

FIGURE 6. a. Deviated well embedded in block reservoir. b. Four deviated offshore wells. c. Tunnel inside a mountain showing tunnel stratigraphy. d. Spiral well for testing of degenerate cases.

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