GEOTHERMAL RESERVOIR SIMULATION:
THE STATE-OF-PRACTICE AND EMERGING TRENDS

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ABSTRACT

Computer modeling of geothermal systems is now a mature technology with application to more than 100 fields worldwide. Large complex three-dimensional models having computational meshes with more than 4000 blocks are now used routinely. Researchers continue to carry out fundamental research on modeling techniques and physical processes in geothermal systems. The new advances are adopted quickly by the geothermal industry and have also found application in related areas such as nuclear waste storage, environmental remediation and studies of the vadose (unsaturated) zone. The current state-of-practice, recent advances and emerging trends in geothermal reservoir simulation are reviewed.

1. INTRODUCTION

With the advent of digital computers, the numerical solution of complex non-linear partial differential equations became possible in the late 1960s. However, the application of these techniques to modeling the behavior of geothermal reservoirs lagged behind their application in groundwater, and oil and gas reservoir modeling. This is not surprising as the coupling between mass and energy transport in a geothermal reservoir adds considerable complexity.

The earliest work on the subject began to appear in the early 1970s. Some further modeling studies were published during that decade, but the effective starting point for the acceptance by the geothermal industry of the usefulness of computer simulation was the 1980 Code Comparison Study which, under the auspices of the US Department of Energy, tested several geothermal simulators on a suite of six test problems (Stanford Geothermal Program, 1980). The results of the study were reviewed during that year's Stanford Reservoir Engineering Workshop. Since then, the experiences of developing site-specific models and carrying out generic reservoir modeling studies has led to a steady improvement in the capabilities of the geothermal reservoir simulation codes. Probably the major thrust of modeling research has been in fundamental studies of the important physical and chemical processes which control the behavior of geothermal and hydrothermal systems.

Coupled heat and mass transfer in the highly heterogeneous environment of a geothermal reservoir involves very complex physical processes. Often phase changes are involved and usually the flow is complicated by the presence of additional chemical species such as gases or dissolved salts. Fundamental studies have resulted in a steady advance of the range of physical phenomena that can be represented in geothermal reservoir modeling, and in improvements in the numerical techniques used in the reservoir simulators. These advances have been quite quickly adopted by geothermal modelers. Thus, some models have used reservoir fluid containing various chemicals and others have included extra features such as a numerical representation of double porosity.

These and other aspects of modeling are discussed in the section on recent advances and emerging trends, below.

The enhanced techniques for modeling geothermal reservoirs have found extensive application in investigations of other complex multiphase, multi-component fluid flows underground, such as nuclear waste storage, mining engineering and environmental restoration.

The use of computer modeling in planning the development and management of geothermal fields has become standard practice during the last 10-15 years. Simulation models have been set up for more than 100 geothermal fields worldwide. The reports on many of these modeling studies remain confidential but from the published work, and personal communications, it is possible to obtain a general picture of the nature of recent models.

The computer power available in the 1980s limited the size of the computational meshes used and many of them were based on geometrically simple models. For example, often two-dimensional models were used, either vertical slices, or single-layer models. In some cases radial symmetry was assumed. These simple models were limited in the detail of the systems they could represent, but often gave good results for the gross behavior of the system and were used to develop the model calibration techniques discussed below. Most of the early three-dimensional models were simplified in some way, usually by omitting low-permeability zones entirely or by using a relatively small number of blocks. During the 1980s, particularly towards the end of the decade, a few quite complex 3D models were developed (e.g., Bodvarsson et al., 1987, 1990a; Ripperda et al., 1991).

The purpose of this paper is to summarize the state-of-practice and to discuss recent advances and emerging trends in geothermal reservoir simulation. Together, these elements comprise the state-of-the-art.

The authors obtained a significant number of personal communications from responses received to an informal questionnaire that was circulated worldwide. The results of this inquiry, as well as an extensive list of references is given in a recent report (O'Sullivan et al., 2000). Due to space limitation most of the references relevant to this paper, as well as tables giving details on models of geothermal systems developed since 1990, are not given here, but can be found in the above-mentioned report which can be downloaded from the Web (http://www-esd.lbl.gov/ER/geodownloads.shtml).

2. CURRENT STATE-OF-PRACTICE

2.1 Conceptual models and data collection

Before a simulation model of a given geothermal field can be set up, a conceptual model must be developed. A good understanding of the important aspects of the structure of the system and the most significant (physical and chemical) processes occurring in it is referred to as its "conceptual

model". It is usually represented by two or three sketches showing a plan view and vertical sections of the geothermal system. On these sketches are shown the most important features such as: surface manifestations (i.e., hot springs, steaming grounds, etc.), flow boundaries, main geologic features such as faults and layers, zones of high and low permeability, isotherms, location of deep inflows and boiling zones, etc.

Setting up a conceptual model requires the synthesis of information from a multi-disciplinary team composed of geologists, geophysicists, geochemists, reservoir engineers and project managers. Some of the raw data require expert interpretation before they can be used. For example, the down-hole temperature logs which are used to construct the isotherm plots are often affected by internal wellbore flows, or the previous production and injection history of the well.

In addition, the data sets tend to be incomplete and often the conceptual models suggested by the various contributing scientists and engineers are inconsistent or incorrect. Thus the "art" of computer modeling involves the synthesis of conflicting opinions, interpretation and extrapolation of data to set up a coherent and sensible conceptual model which can be developed into a computer model.

2.2 Model design

Model structure
Recent models have a complex 3D structure and often consist of as many as 3000-6000 blocks or elements. Even with these large site-specific models, the smallest block size is still quite large. A typical minimum horizontal dimension is 200 m and a minimum vertical dimension is 100 m. The problem of how best to represent the fractured rock in a geothermal reservoir with large blocks has received a considerable amount of attention. Most modelers have simply used a porous medium approach while a few have used double porosity or MINC (Pruess and Narasimhan, 1985) models. Others have included explicit representation of a few dominant fractures and faults.

In some special cases the presence of small volume high-permeability fractures in a generally low-permeability matrix has an important effect on the reservoir behavior and the simple porous medium approach is not adequate. For example, the production of a high-enthalpy, steam-water mixture from a high-pressure liquid reservoir requires the representation in the model of boiling in fractures. Similarly the rapid transmission of a tracer along fractures in a geothermal reservoir cannot be accurately represented by a single porous medium model.

A few modelers have set up fracture network simulators which are all somewhat simplified and cannot handle multiphase flow or mass flow in the matrix. Also simple methods for characterizing a fracture network are not available. The fracture network approach has been applied to studies of some hot dry rock (HDR) projects (see for example, Hayashi et al., 1999). HDR reservoirs are simpler to model in some respects because all the reservoir fluid is liquid water and no convection occurs in the pre-exploitation state. On the other hand, the presence of fractures is important and even early HDR models have consisted of a large number of blocks, with very small blocks in and near the main fracture.

The use of large blocks in a geothermal model also makes the task of matching well-by-well performance difficult. Some modelers have overcome this difficulty by introducing embedded sub-grids around each well.

The most common simulators which have been used to implement these complex 3D models are STAR (Pritchett, 1995), TETRAD (Vinsome and Shook, 1993) and TOUGH2 (Pruess, 1998), although a few other codes have also been developed and used.

A regular rectangular mesh structure is required by TETRAD and STAR, whereas TOUGH2 can handle general unstructured meshes. However, most geothermal models set up using TOUGH2 have some structure such as layering.

The major codes all have the capability of handling multiphase, multi-component flows, and several models have included a reservoir fluid which is a mixture of water and carbon dioxide or a mixture of water and NaCl or both.

Boundary conditions
Two important matters to be decided in setting up a model of a geothermal system are its size and the boundary conditions to be applied on the sides of the model.

Geothermal systems, apart from low-temperature systems, involve large-scale convection of heat and mass, driven by deep heat (and fluid) recharge. Usually the whole of this convective system is not included in a model and therefore aspects of the convective system must be represented by the boundary conditions. In particular at the base of the model the deep upflow is represented by a suitable source of heat and mass. The only exception to this procedure is the special case of vapor-dominated systems where it is not possible to set up a stable natural state using flow boundary conditions. Instead constant pressure and vapor saturation boundary conditions must be applied.

Constant pressure and temperature boundary conditions instead of flow boundary conditions have been used for modeling hot water or liquid-dominated, two-phase systems. This procedure works satisfactorily but should be used with care as it may lead to a spurious quasi-steady state in future scenario simulations where the unlimited recharge from a constant pressure boundary matches the specified production rate.

At the lateral boundaries of the model a number of strategies have been adopted. In general it is advisable to have the side boundaries of the model sufficiently remote from the production and injection zones so that the choice of boundary conditions does not significantly affect the performance of the model over the simulated lifetime of the project (say, 25 years). Some modelers have implemented no-flow (heat and/or mass) boundary conditions, while others have applied background linear temperatures and hydrostatic pressures, or other constant temperature and pressure "open" boundary conditions. The latter case allows the free flow of cool water into (or out of) the model. An intermediate approach adopted by some is to apply "recharge" boundary conditions which allow mass flow into (or out of) the boundary blocks at a rate proportional to the pressure drop (or increase).

In some instances much more "active" lateral boundary conditions have been applied by specifying mass injection or production at some of the boundary blocks. This approach was common when the limited power of computers restricted the number of blocks which could be used in a model, and hence its total size. The problem with this technique is that the flows and hence the temperature distribution in a natural-state model can then be matched by adjusting the boundary conditions. The flows do not have to be consistent with the

permeability structure. Thus, this process makes the external application of the lateral flows or constant pressure and temperature boundary conditions by the modeler the dominant part of model calibration.

In the opinion of the authors, the model should be self-contained as much as possible, with the model structure determining its behavior and not the lateral boundary conditions. If these conditions have a large influence on the behavior of the model it means that the modeled domain is not large enough and the lateral boundaries of the model should be pushed farther out.

For the top boundary there are examples where the model was truncated well below the ground surface, and either a closed top (no flow of heat and/or mass) corresponding to a low-permeability layer/caprock, or an open top with a constant pressure and temperature, was implemented. Probably the most common approach is to assume a constant atmospheric pressure and temperature at the top of the model. In most cases these atmospheric conditions are implemented not at the ground surface but at the estimated position of the water table. Some modelers have used an approximate flat water table at a constant elevation while others have adjusted the thickness of the top blocks of the model to match the variable elevation of the water table.

The difficulty with using a top boundary condition of constant atmospheric conditions is that it allows the unlimited inflow of cold water or the unlimited outflow of warm fluids, depending on whether the pressure in the top block decreases or increases, respectively. In fact the inflow of cold water cannot exceed the natural infiltration rate. In a real geothermal system, if the shallow pressures fall far enough, the water table will be lowered as well as water being drawn in. There is no way of representing this lowering of the water table in a standard geothermal model. Also the shallow temperature regime may not be well represented by a single atmospheric temperature at the water table level. Some have added complexity by estimating the variable temperature at the water table and implementing constant pressure and temperature conditions with a different temperature at each block at the top of the model.

The relatively large size of blocks in present computational meshes prevents modeling of the direct flow from depth to small surface features such as hot springs and steaming ground. Several models have used artificial wells, located in near surface layers and operating on deliverability to represent surface features.

Recently, some modelers have tried to improve the representation of the shallow zone in a geothermal field by including the unsaturated zone. This was carried out by making the reservoir fluid a mixture of air and water, and then applying atmospheric conditions at the ground surface. The unsaturated zone, between the ground surface and the water table, then appears as blocks with a high mass fraction of air, whereas in the saturated zone the mass fraction of air is very low. This approach is an improvement on the standard method of including only the saturated zone, but it is still approximate as the resolution of the movement of the water table is limited by the thickness of the top blocks. To obtain high accuracy either a number of very thin layers would have to be used at the top of the model, or alternatively, a new technique for tracking the movement of the water table, similar to that used for modeling unconfined flow in a groundwater aquifer, could be developed.

Calibration

A general procedure for model calibration has been developed. It consists of natural-state modeling followed, if possible, by history matching. Most modelers have carried out at least the first step of the natural-state modeling procedure which consists of running the model for a long time in a simulation of the development of the geothermal field over geological time. The temperature distribution and surface outflows of heat and fluid (water and steam) in the model are compared with measured field data and the permeability structure of the model is adjusted to achieve a satisfactory match. The magnitude and location of the deep hot upflow may also need to be adjusted. The calibration of the natural state may require many iterations before a good match to the observed data is achieved.

The geothermal fields for which models have been set up recently vary widely in terms of their state of development. Some have been operating for many years and some have a very short or no production history. A second matching stage of calibration has been carried out for most systems which have some production history. It is aimed at matching the measured behavior of the geothermal field to exploitation with the simulated response. In this process the past production for the wells is assigned to the relevant blocks in the model (based on information about the locations of the feedzones) and a simulation of the exploitation period is carried out. The pressures and temperatures in the model at the start of production are taken from the natural-state model.

The model results for pressure changes are then compared to measured data and adjustments made to permeabilities and porosities, if necessary. Also production enthalpies from the model are compared with field data. For hot-water systems where the injection zone is well separated from the production zone, the enthalpies of the produced fluids change slowly. Therefore for reservoirs with only a few years of production history, enthalpies may not be useful for calibration. Similarly in vapor-dominated systems, production enthalpies remain almost constant and pressures change slowly and so calibration by history matching is not possible if only a short production history is available.

For two-phase reservoirs, or hot-water reservoirs near their boiling point, the discharge enthalpy depends on the reservoir permeability and porosity and the production rate. Several modelers have used the matching of short- and long- term enthalpy transients to assist with model calibration.

Recently tracer-test results or chemical changes have been used to assist model calibration. Tracer-test data are particularly useful for calibrating models of highly fractured reservoirs such as Dixie Valley, USA where the rapid return of injectate is an important phenomenon.

A few modelers have used geophysical data such as gravity measurements or electro-potentials to evaluate the accuracy of a model.

The process of model calibration both for natural-state and past-history matching is laborious. It is sometimes difficult to decide which part of the model structure should be adjusted to improve the match to a particular field measurement. Some use of computerized model calibration has been made in improving a few geothermal models. In this case, the computer is used to systematically adjust a few parameters until the differences between model results and field data are

at a minimum. It is demanding in terms of computer time and requires certain manual intervention to select the particular parameters to be adjusted.

Modeling experience
The main use of computer models has been in estimating the electricity generating potential of undeveloped geothermal fields, or for evaluating expansion options for partly developed fields. Also modeling has been extensively used for investigating different fluid production and injection scenarios. In a few cases, (e.g., Salton Sea, USA) modeling has been used to investigate geochemical evolution and mineral recovery from spent brine.

Most of the largest and most complex models are too recent to evaluate by comparing their predictions with the actual outcome. For many of the older models, the scenarios considered at the time when they were set up are different from the way the system was subsequently operated and therefore a detailed comparison between model predictions and the actual outcome is not possible. However, for some of the older and smaller models this comparison can be made.

The most comprehensive evaluations of models in this manner published in the open-file literature are those of Olkaria, Kenya and Nesjavellir, Iceland geothermal fields. Similar assessments of model predictions have been performed by operators (and their consultants) for many fields, but are mostly considered to be proprietary information. Some of these studies have been described in brief conference papers (e.g. Antúnez et al., 1991; Pritchett et al., 1991; Menzies and Pham, 1995; Pritchett and Garg, 1995; White et al., 1997; O'Sullivan et al., 1998).

For the Kenyan system, a set of earlier predictions were evaluated using three years of data collected following a 1987 modeling study. The Olkaria East Field is interesting and difficult to model because it contains a vapor-dominated zone underlain by a liquid-dominated region. In the initial study, five scenarios were devised for field exploitation involving well spacing, injection, and power generation strategies. Thirty-year forecasts of field production were made although it was recognized that predictions were likely only to be valid for as long as the period of the matched history, in this case 6.5 years.

In the post-audit (Bodvarsson et al., 1990b), a well-by-well comparison was performed, with the conclusion being that the model adequately predicted steam rates and their decline for about 75% of the wells, with some wells showing unorthodox behavior and others having little history on which to base the calibration. Using a field-wide basis for comparison, the total steam rate decline agreed very well with the prediction. The model also forecasted the relative contribution of different feed zones to the wells fairly well. Following the comparison, further calibration of the model was performed and predictions were again made for a thirty-year period.

For Nesjavellir, flow rate, pressure and enthalpy data for the period 1975-1985 were used to calibrate a relatively simple 3D model. Comparisons of the model predictions with measured data for the period 1987-1992 showed good agreement for the flow rates and enthalpies, but the model overestimated the pressure decline (Bodvarsson et al., 1993).

3. RECENT ADVANCES AND EMERGING TRENDS

In this section we review new developments in geothermal reservoir simulation that are used in research and are currently being introduced into engineering practice.

Improved process description
In early geothermal reservoir simulations the reservoir fluids were idealized as pure water. Subsequent more realistic representations of geothermal fluids included carbon dioxide, which usually is the most prominent non-condensible gas, and dissolved solids, typically represented as NaCl.

Later developments include interactions between several different dissolved and gaseous chemical species in geothermal flows, and porosity and permeability changes from dissolution and precipitation of minerals. More sophisticated multi-species chemical models, that describe reactions between aqueous, gaseous, and solid species, have usually been limited to zero-dimensional systems in which no flow and transport effects are taken into account. A fully-coupled treatment of 3D fluid flow and mass transport with detailed chemical interactions between aqueous fluids, gases, and primary mineral assemblages is very difficult. Such treatment can potentially provide a more realistic description of geothermal reservoir processes during natural evolution as well as during exploitation, and can provide added constraints that can help reduce the inherent uncertainty of geothermal reservoir models.

Ongoing research is exploring different approximations for coupled processes with vastly different intrinsic time scales, and is addressing uncertainties in thermodynamic parameters, reactive surface areas and kinetic rate constants. Besides theoretical and computational limitations, a lack of adequate data to calibrate against limits the applicability of the models.

Natural and man-made tracers, such as soluble and volatile chemicals, noble gases and isotopes, are increasingly being used for determining fluid flow paths and reservoir processes. As indicated earlier, tracer data have become very helpful in the calibration of geothermal models.

New higher-order differencing methods provide improved resolution of sharp fronts and accurate modeling of advective transport. Approaches are being developed for modeling the migration of reactive tracers, including: (1) volatile chemicals that partition between liquid and gas phases, (2) tracers that show thermal degradation and thereby can provide early warning of cooling effects from injection, and (3) isotopes that are subject to rock-fluid interactions.

Several groups are working on extending the thermodynamic range of fluid property descriptions, especially to the higher (super-critical) temperatures needed for modeling deep zones in geothermal systems (see for example, Yano and Ishido, 1998).

While coupling between fluid flow and rock stresses is not normally addressed in the modeling of hydrothermal systems, such coupling is essential in enhanced geothermal systems and hot dry rock geothermal reservoirs. Simulation models and applications for coupled thermal-hydrologic-mechanical processes have been presented by several authors.

High-resolution and stochastic techniques borrowed from the extensive literature on stochastic hydrology are being adopted for improved description of reservoir heterogeneity.

Model calibration

Major advances have been made in the development of automatic history matching (model calibration) capabilities, using inverse modeling techniques (Finsterle et al., 1997). These methods replace the tedium of manual model adjustment by trial-and-error with an automated process that obtains optimal model parameters by computer. In addition to streamlining the model calibration process, inverse techniques provide quantitative model acceptance criteria, potentially leading to more reliable models with less subjective bias. The increased computational demands of inverse modeling have prompted the development of parallel processing techniques, not only for high-end massively parallel platforms, but also for clusters of low-cost workstations or personal computers.

Geothermal reservoir models have usually been constrained by natural-state modeling and well-test analyses, and have been calibrated against reservoir engineering-type data (i.e., flow rates and enthalpies of wells, reservoir pressures and temperatures), as well as geochemical data (gas content and salinity changes). A relatively new trend is the utilization of geophysical and geochemical observations for model calibration, such as resistivity and microgravity changes, self-potential, microseismics, and tracer data.

Numerics and graphics

In addition to the areas highlighted above, improvements continue to be made in numerical algorithms, to be able to solve larger reservoir problems more efficiently. Enhanced user features include coupling between reservoir and wellbore flow with capabilities for flexible, dynamic scheduling of production and injection wells. Graphical user interfaces are being developed that integrate simulation and grid generation capabilities, and preparation and visualization of input and output data

4. DISCUSSION AND CONCLUSIONS

As discussed above, geothermal reservoir simulation is a fully developed technology that is routinely used in reservoir engineering practice. Large complex 3D models are used and often include the presence of dissolved salts or noncondensible gases. The tasks of dealing with such large complex models has been made easier by the use of computerized calibration techniques and graphical interfaces.

Important advances continue to be made to achieve a more accurate and comprehensive representation of reservoir processes, to reduce the uncertainties in models, and to enhance the practical utility and reliability of reservoir simulation as a basis for field development and management.

Beyond the practical needs of reservoir engineering, there is a continuing quest from earth scientists to improve our knowledge of hydrothermal systems and their natural evolution. This requires more comprehensive understanding and modeling of coupled processes than is commonly done in standard reservoir engineering practice. Geothermal reservoir simulation has pioneered approaches for modeling non-isothermal multiphase flows, and has provided important spin-offs for research on nuclear waste disposal, environmental remediation, vadose (unsaturated) zone hydrology, and thermally enhanced oil recovery. Advances in those fields are now providing capabilities that may benefit the practice of geothermal simulation.

5. ACKNOWLEDGMENTS

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