PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2008
SGP-TR-185

PRODUCTION CAPACITY ASSESSMENT: NUMERICAL MODELING OF GEOTHERMAL RESOURCES

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ABSTRACT

In this study a deterministic modeling approach is developed for numerical simulation of geothermal resources, for assessment of production capacity. The simulator iTOUGH2 (i.e. Inverse modeling of Transport Of Unsaturated Groundwater and Heat) is used, for which comprehensive pre- and post-processor have been designed. The processors facilitate the creation of discrete irregular grids, visualization of physical conditions and visualization of convective pore velocities in the reservoir. The postprocessor also compares observed field data with the transient model response. The simulator optimizes selected parameters, minimizing the residual of observed and calculated response. Sensitivity and error analysis indicate whether high parameter correlations are present, which can indicate over-parameterization. The Svartsengi geothermal system in SW-Iceland, is used for model validation. Results show good agreement between the model and the reservoir response to production. Comparison to other models indicates that the present model is a potential alternative to the earlier models.

INTRODUCTION

Different approaches have been applied in resource assessment of high-temperature geothermal fields in Iceland, e.g. volumetric, analytical and numerical approaches (Ketilsson, 2007). In the volumetric approach recoverable reserves are estimated as a fraction of the energy initially in place. The essential weakness of the method is the assumption of a fixed recovery factor, while real energy recovery strongly depends on the physical conditions and properties of the reservoir (Parini and Riedel, 2000). Numerical models can take these physical aspects into account, aspects that can be matched with production response histories and other observational data (Bodvarsson and Witherspoon, 1989). Analytical methods have also been developed but lack comprehensive physical description of the complex geothermal resources (O'Sullivan et al., 2001).

The numerical models are of varying degree of complexity, i.e. from simple lumped parameter models (Bodvarsson and Witherspoon, 1989; Axelsson et al., 2005) to more complex distributed parameter models, each having the possibility of representing unique physical conditions and properties (Bjornsson et al., 2003). Lumped parameter models can readily match production response histories with acceptable accuracy but the underlying weakness of this approach is that it neglects the geometrical structure of the geothermal systems and the details that can be simulated by well-by-well models. On the other hand, the weakness of the well-by-well approach is its complexity. If individual wells are to be modeled using complicated production histories then the heterogeneous and complex geometrical structure has to be modeled in detail, but such details are often unknown. This detailed complexity is likely to result in over-parameterization, i.e. high direct correlation between parameters within the model (O'Sullivan et al., 2001).

The aim of the work presented here was to develop a modeling technique that addresses the drawback of the volumetric approach as well as avoiding the complex and time consuming well-by-well approach. Thus, a deterministic modeling technique has been applied to numerical simulation of geothermal reservoirs without constraining it to great details. The, technique was also made as general as possible while representing the overall physical characteristics of a high-temperature reservoir. The program iTOUGH2 (i.e. Inverse Transport Of Unsaturated Groundwater and Heat) is used, for which comprehensive pre- and postprocessor have been designed. The processors facilitate the creation of discrete grids and input files for iTOUGH2 as well as visualization of flow patterns, temperature, pressure and saturation distributions using the program MATLAB. The data can be presented both at certain discrete points in time and also as animations (Trauth, 2006).

A case study involving the Svartsengi geothermal field is used for model validation. Previous models of Svartsengi are based on varying fundamental physical assumptions. Bodvarsson presented in 1988 a radial model using the numerical simulator MULKOM (Pruess et al., 1999). The model includes the effect of a two phase zone overlying a liquid reservoir. The model incorporates both energy and mass balance, and other rock property effects, as the present study does. Bodvarsson also made a comparison with four analytical studies by Kjaran et al. (1980), Regalado (1981), Gudmundsson and Olsen (1987) and Vatnaskil (1983). Those models do not consider energy balance, the presence of the two-phase zone or variations in rock properties in the reservoir. In 1989 Vatnaskil presented a finite element model which has been updated regularly (Myer and Kjaran, 2007). In 1998 Bjornsson developed a radial model concentrating on various production scenarios from the two-phase zone (Bjornsson, 1999).

The paper is organized as follows. After description of fundamental assumptions, theory behind the simulator and the pre- and postprocessors (Methods) the modeling approach is validated (Model Validation). In the final section (Conclusions) the broader implications of the results are discussed.

METHODS

Physical Characteristics

A geothermal reservoir is characterized by physical conditions and properties. The physical conditions of a single phase reservoir are defined by pressure P and temperature T. For two phase reservoirs P and T are dependent variables, thus either enthalpy h or mass fraction χ are used to further specify the exact conditions in the reservoir. The relevant physical properties of the reservoir are; (1) permeability of the formation, i.e. the ability of a material to transmit fluids k, (2) porosity φ i.e. fraction of void spaces in a material, (3) relative permeability $k_{r,}$ defined as the ratio of the phase permeability (i.e. liquid or vapor) over the permeability of the porous medium, (4) thermal conductivity λ which controls heat transfer by conduction and (5) heat capacity C, which determines the amount of stored energy (Bodvarsson and Witherspoon, 1989).

Mass- and Energy Balance

The simulator iTOUGH2 is used to simulate non-isothermal flow of a single component (water) in two coexisting phases (liquid, vapor). The simulator uses both mass and energy balance equations, derived as a multiphase volume balance equation for a given domain. The transport of mass and energy involves flux in the form of diffusion and convection as well as sources and sinks, which is also related to changes in time. The governing equations are discretized in space based on an integral finite difference formulation. Time is discretized fully implicitly, with a first-order finite difference approach. This discretization results in a set of nonlinear coupled algebraic equations which are solved simultaneously by the means of Newton-Raphson iterations (Pruess et al., 1999).

Parameter Estimation

When a model simulation is performed, physical characteristics are specified in a numerical model along with appropriate initial and boundary conditions. The resulting model calculations can then be compared with observed data in order to suggest improvements. This is done automatically in iTOUGH2 using minimization algorithms to find the minimum of the difference between model results and data by iteratively updating selected parameters of the model. In this study minimization of the model error is based on the Levenberg-Marquardt algorithm (Gill et al., 1978). The Parallel Virtual Machine (PVM) software is used to solve the parameter estimation problem in a cluster of computers (Finsterle, 2000).

Model Criteria

One of the key advantages of the parameter estimation approach described is the possibility to perform error- and sensitivity analysis, because a good match does not necessarily mean that the estimates are reasonable. They may be highly erroneous due to high parameter correlation, which is usually an indication of over-parameterization (Finsterle, 2000).

The covariance matrix of the estimated parameters can be analyzed to obtain correlation coefficients and parameter combinations that lead to similar matches of the observed data. In order to make sensitivity coefficients comparable with one another, the Jacobian matrix from the parameter estimation is scaled by the ratio of the standard deviation of the observation and the expected parameter variation. The overall contribution of each data set and estimation of contribution of each parameter can then be found. Also, by measuring the change in the objective function through parameter perturbation, the contribution of each parameter can be estimated. Other model criteria are applied as shown in e.g. the goodness-of-fit of the solution with the error variance, which represents the variance of the mean weighted residual. The interpretation of the covariance matrix also provides the key criteria to evaluate the modeling results. The covariance matrix not only shows potentially high estimation uncertainties, resulting from insufficient sensitivity of the observed data, but also reveals correlations among the parameters that may prevent an independent determination of certain properties of interest (Finsterle et al., 1999; Finsterle, 2000).

Model Preprocessor

Several preprocessors for iTOUGH2 exist today, e.g. PETRASIM, GEOCAD, MULGRAPH and WIN-GRIDDER, but their capabilities are limited. Therefore, most modelers have created their own environment, e.g. in the form of shell scripts (O'Sullivan et al., 2001). The preprocessor designed here uses the programming software MATLAB and the program AMESH for mesh generation using Voronoi tessellation (Haukwa, 1998).

The preprocessor has an interactive approach for creating a discrete grid for a given reservoir, where the user supplies e.g. locations of wells and other geographical information. By using Voronoi tessellation in MATLAB the user can then refine the grid by removing or adding points and the resulting tessellation is redrawn instantly. Other functions facilitate the definition of initial and boundary conditions, physical conditions and creation of necessary input files for iTOUGH2.

Model Postprocessor

As for the preprocessor a number of postprocessors exist today as outlined by O'Sullivan et al. (2001). Due to the fact that some are unable to handle unstructured grids while others are unable to view certain aspects of the results, e.g. convection pattern, saturation etc., a postprocessor was designed as part of the work presented here. The postprocessor can handle both unstructured and structured grids with any type of a grid naming system. It imports the data into MATLAB and stores it in arrays that are interpolated into a structured, three dimensional grid thus enabling easy interpretation of horizontal and vertical slices through the reservoir in one, two or three dimensions. In order to visualize the pore velocity in the reservoir, an algorithm has been developed to transform the velocity between neighboring polygons to a single velocity vector for each polygon (Trauth, 2006).

MODEL VALIDATION

Measured field data from the Svartsengi geothermal field in SW Iceland are well suited for testing exploitation models and numerical modeling methods. The field has been under exploitation since 1976 and has a well documented production and pressure drawdown history. Fluid from the reservoir has been used to heat groundwater, which is then transported by pipelines to nearby towns and villages for space heating. The geothermal fluid is also used for electric power generation. In 2006 the Svartsengi power-plant had an installed capacity of 46,4 MW of electricity (Palmason, 2005).

Svartsengi Conceptual Model

Conceptual models of the Svartsengi system, describing physical conditions and characteristics, have been developed by several authors (Eliasson et al., 1977; Kjaran et al, 1980; Regalado, 1981; Bodvarsson, 1988; Bjornsson, 1999; Bjornsson and Steingrimsson, 1992). The reservoir is believed to extend down to 2500 m where heated brine ascends due to buoyancy forces developing a convection cell (Kjaran et al., 1980). The convection is believed to be hindered by a caprock at a depth of 300-500 m, as postulated by Franzson (1995), formed by filling of pores with alteration minerals, which precipitate when the geothermal brine cools down.

The subsurface rocks at Svartsengi mainly consist of basalt lavas and basaltic hyaloclastites. The high-permeability reservoir is primarily associated with strata boundaries, fractures, and boundaries of intrusions (Franzson, 1995). Bjornsson and Steingrimsson (1992) present a study of over 250 temperature logs that results in a good determination of the formation temperature. The analysis identifies three different aquifer systems within the Svartsengi reservoir, i.e. (1) the warm groundwater system at 30-300 m depth, (2) the main reservoir system at depths greater than 600 m and (3) a two-phase chimney in the NE-part of the well field, overlying the liquid reservoir.

The production response of Svartsengi has been monitored for thirty years, i.e. during 1976-2006, as reviewed in (Myer and Kjaran, 2007). Using estimated yearly average production and injection rates, a stepwise idealization of the data has been constructed. As shown in Fig. 1 (a) the production history is idealized by three steps. Similarly injection is idealized by two steps. An interpolation of the pressure drawdown history of the system, based on data from three wells, is shown in Fig. 1 (b). It uses a cubic spline interpolation of selected data points. This simple approximation of the production, injection and pressure drawdown history is not believed to affect the modeling results significantly, as it is well known that variations in production rates are averaged out in the pressure response.

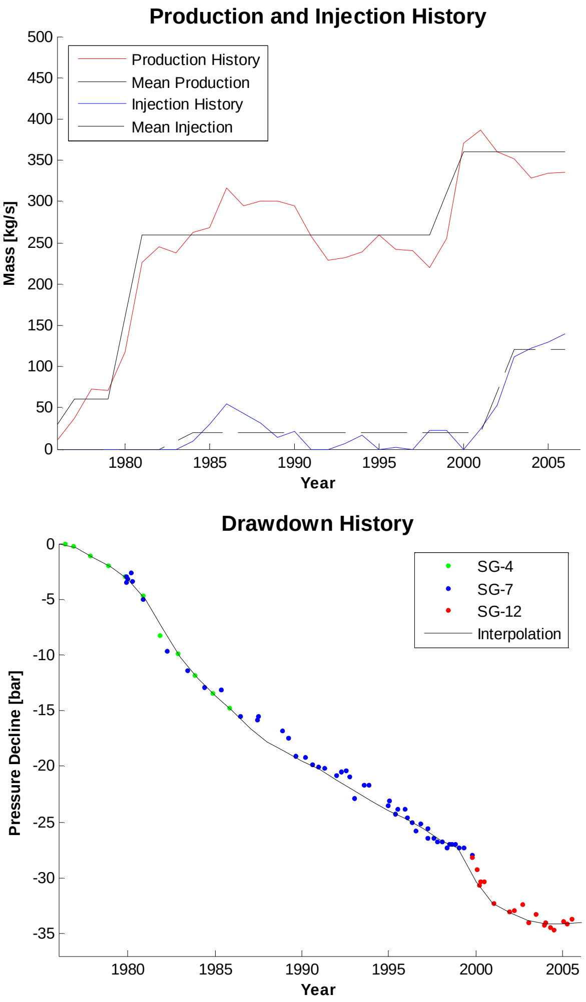

Fig. 1. (a) Production and injection history of Svartsengi. (b) Drawdown history of Svartsengi. Interpolated well data are shown by black lines.

Numerical Model

The Svartsengi model-mesh used in this work has nine layers, each with 169 elements covering a volume with horizontal dimensions of 100x100 km and 2700 m depth seen in Fig. 2. The mesh therefore has 1521 elements in total, of which 338 are inactive since the top and the base layers have constant physical conditions. Initial physical reservoir conditions are set by a temperature gradient of 100°C/km with a corresponding hydrostatic pressure gradient. This is a common approach as seen e.g. in (Bjornsson et al., 2003).

The physical boundary conditions can be seen in Fig. 4. The lateral sides allow cold fluids to enter into the model according to the pressure decline within the boundaries. A low permeability layer surrounds the two-phase chimney at 300-600 m b.s.l., simulating the low permeability hyaloclastite series. The constant physical reservoir properties used in the Svartsengi model are listed in Table 1, based on Bodvarsson (1988), Bjornsson (1999) and Bjornsson et al. (2003). Linear relative permeability curves are used with immobile liquid and steam saturations of 40 and 5%, respectively.

Table 1: Physical properties in the Svartsengi model.

Physical Properties	Values
Rock density	2650 kg/m3
Heat capacity	900 J/kg°C
Porosity	10%
Thermal conductivity	2 W/m°C
Relative water permeability	40%
Relative steam permeability	5%
Caprock permeability	0.001 mD
Bedrock permeability	~0 mD

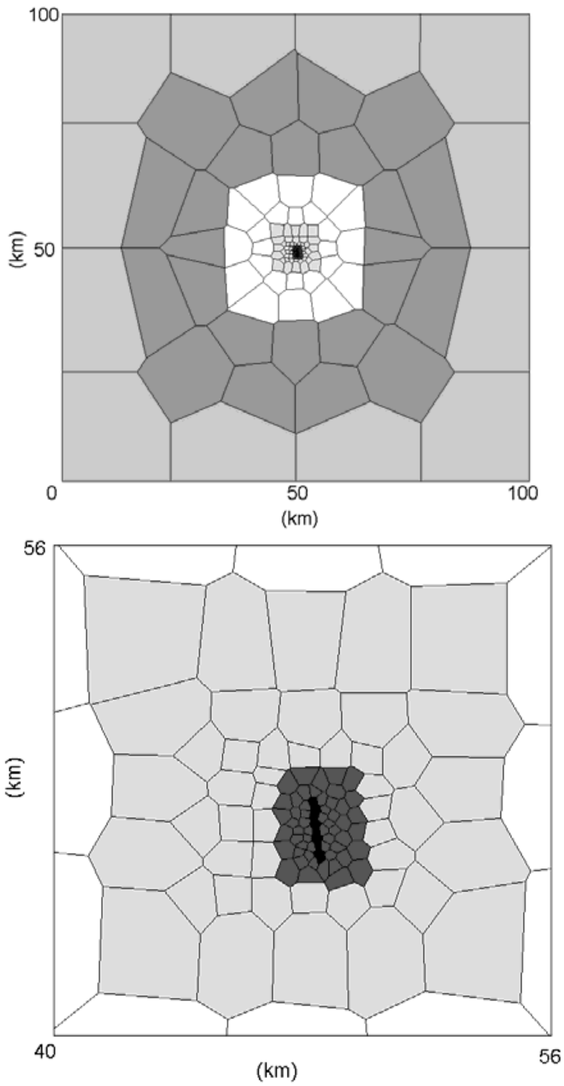

Fig. 2. The horizontal element and material distribution of the Svartsengi mesh. An enlarged area of the central reservoir is shown in the lower part of the figure.

Numerical Results

Within the high permeability reservoir isotropic permeability of 100 mD was selected as an initial guess for the 2100 m thick section. Surrounding the reservoir, an isotropic permeability of 5 mD was selected as an initial guess for a 1800 m thick section. Recharge of 93 MW of heat represents natural recharge into the reservoir.

Five observations where used as indicators of a decrease in the objective function; pressure drawdown with 1 bar deviation, enthalpy of the produced fluid with 20 kJ/kg deviation, reservoir temperature at 1050 and 1350 m b.s.l. and surrounding temperature with deviation of 2°C. Residuals of the observations and the calculated response of pressure drawdown and reservoir temperature can be seen in Fig. 3.

Four parameters where chosen for optimization; injected fluid enthalpy, energy flux, productivity index of fumaroles and permeability of the reservoir and surroundings. The main features of the model and the best estimate parameters are shown in Fig. 4. The overall contribution to each observation indicates that reservoir temperature and pressure are the most sensitive ones.

The contribution of each parameter to the objective function, measured by perturbation, indicate that the enthalpy of the injected fluid is the most contributing one, followed by the reservoir permeability, whereas other parameters do not contribute significantly. The relative parameter sensitivity shows that the permeabilities are the most sensitive ones. The residuals are outside the deviations specified according to the goodness-of-fit of the solution. The covariance matrix shown in Table 2, indicates that the variance of the enthalpy of injected fluid is high along with that of the energy flux.

Vertical and horizontal sections of the reservoir in 1976 and 2006 are shown in Figs. 5 and 6, illustrating the effect of production.

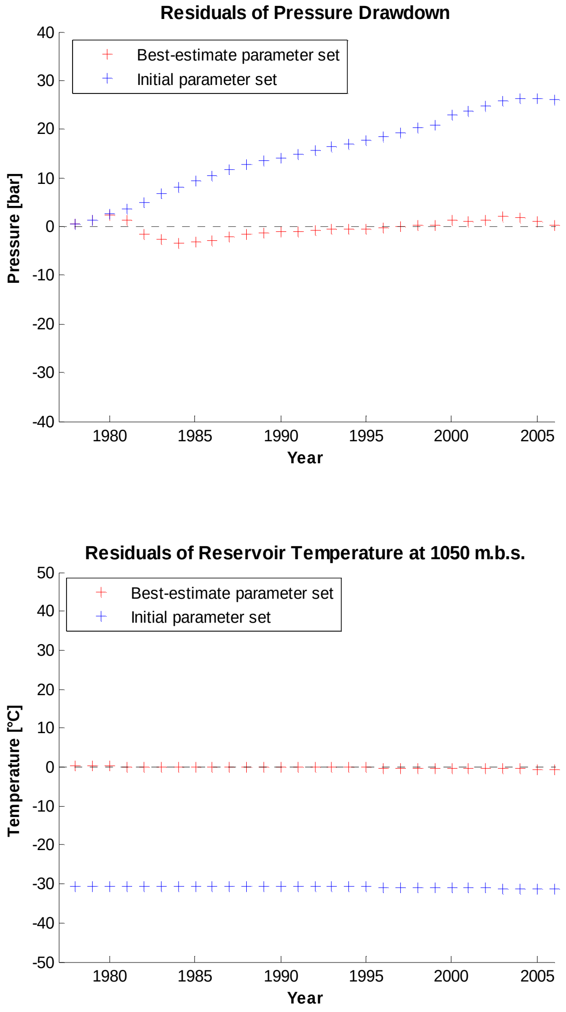

Fig. 3. Residuals of pressure and temperature responses and observations, for initial and best parameter values.

Table 2. Estimation covariance matrix for the Svartsengi model. The diagonal contains variances, the lower triangle is the covariance matrix and the upper triangle is the correlation matrix.

	Surrounding permeability	Reservoir permeability	Productivity index	Enthalpy of injected fluid	Energy flux
Surrounding permeability	~0.0	-0.5	0.6	0.2	-0.6
Reservoir permeability	~0.0	0.1	0.1	0.4	0.0
Productivity index	0.3	-0.1	15.6	0.8	-1.0
Enthalpy of injected fluid	802.4	2567.0	$0.9\cdot10^{5}$	$0.8\cdot10^{9}$	-0.8
Energy flux	-0.9	0.1	-39.8	$-2.2\cdot10^{5}$	102.1

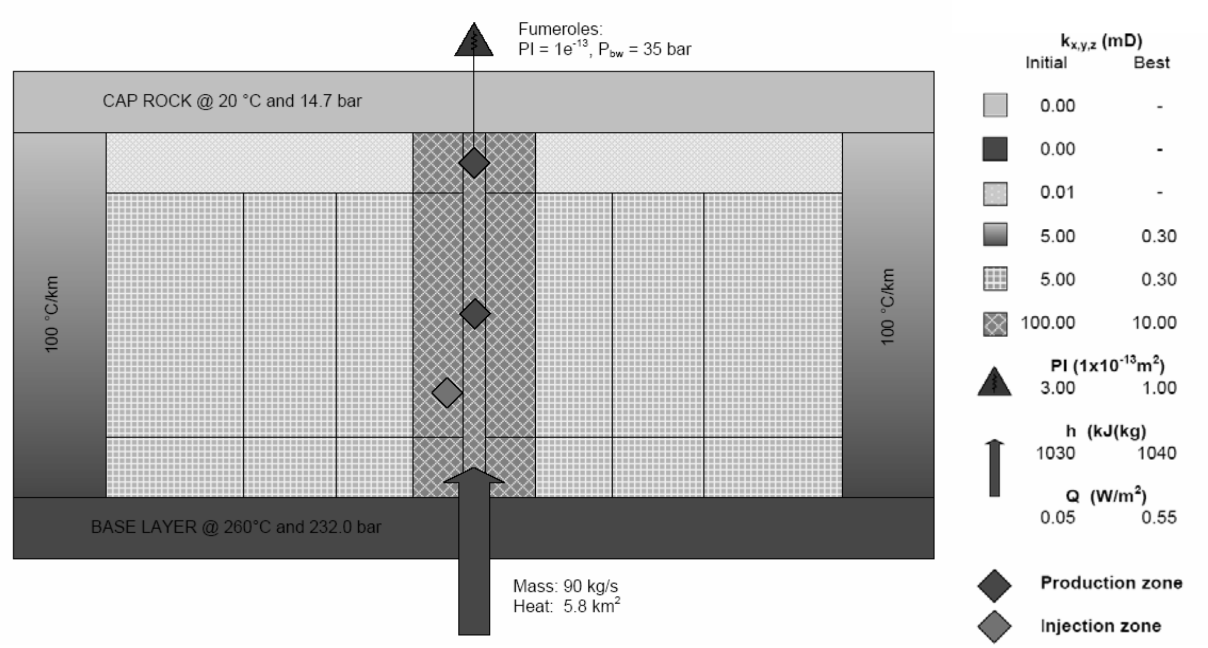

Fig. 4. Physical characteristics of the Svartsengi model. Initial and optimal values of the five parameters are shown on the right.

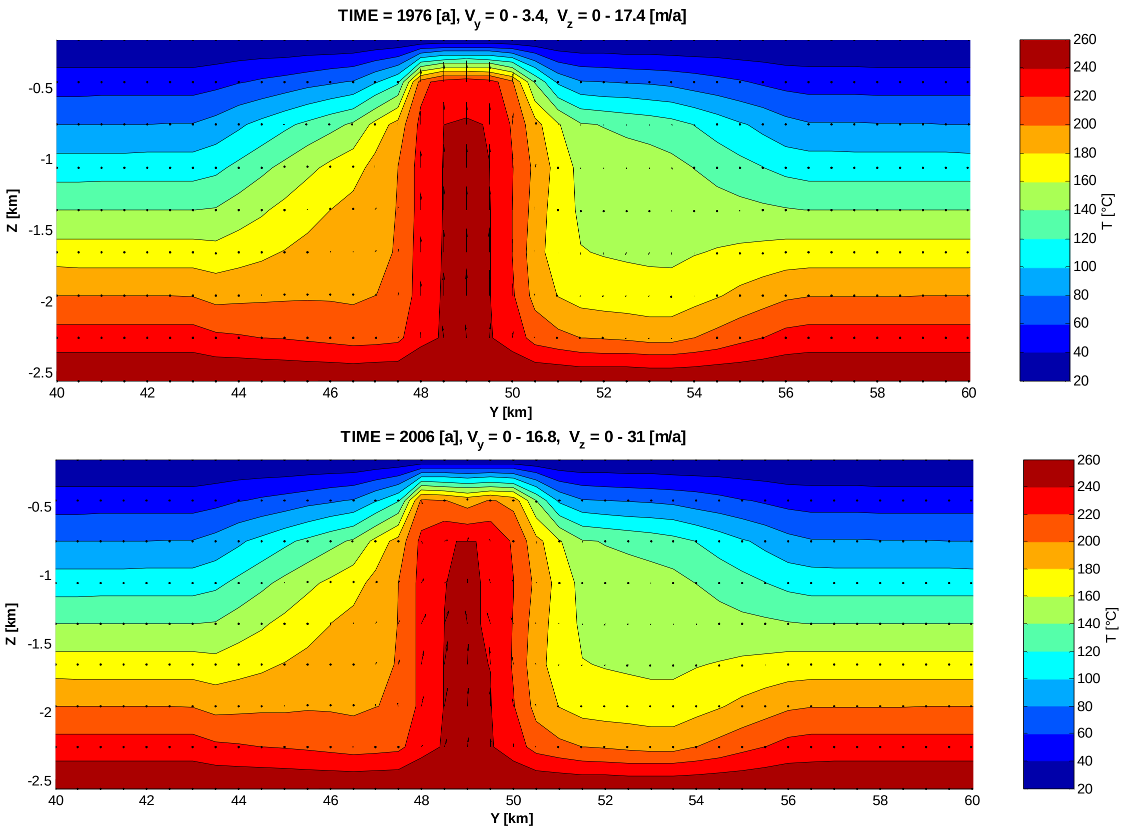

Fig. 5. Vertical section of temperature distribution before (1976) and after (2006) 30 year production at Svartsengi (X = 50 km). The change in flow pattern is a result of pressure drawdown due to production.

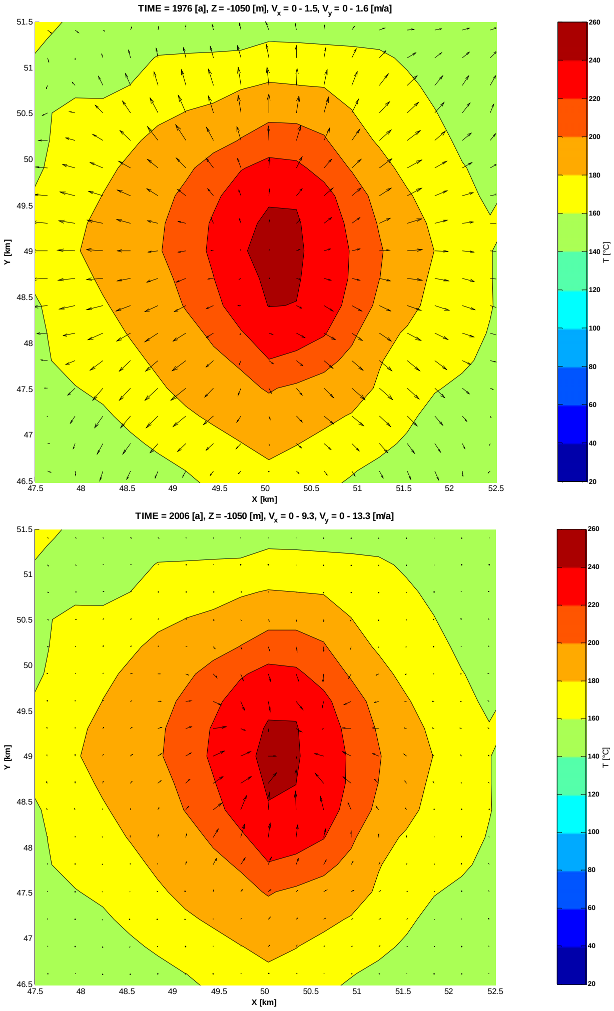

Fig. 6. Horizontal section of temperature distribution before (1976) and after (2006) 30 year production at Svartsengi. Flow changes from outward to inward are due to pressure drawdown.

Comparison with other models

For comparison the production history as shown in Fig. 1 (a) is changed to a single step 200 kg/s production for 25 years of exploitation. The pressure drawdown predicted by Bodvarsson (1988), Kjaran et al. (1980), and Regalado (1981) can then be compared to the results of the present study as shown in Fig. 7. All the models have an average production rate of around 200 kg/s. Comparison shows a greater drawdown in the present study at the beginning, but it becomes similar to Kjaran et al. and Regalado after 25 years of production. Bodvarsson on the other hand predicted a much smaller pressure drawdown. In addition, Bodvarsson predicted a considerably less decline than the model of Gudmundsson and Olsen (1987). Bodvarsson observed that models that only allow one-sided recharge, such as those by Kjaran et al. and Regalado, predict the largest pressure decline. This is followed by the two-sided recharge model by Gudmundsson and Olsen and finally a more gradual pressure decline in the Bodvarsson model, which does not impose any impermeable boundaries. The two cell boiling zone model by Vatnaskil (1989) predicts the largest drawdown of all the models discussed here. These results clearly demonstrate the importance of a good conceptual model and the need for caution when assumptions for the system are made.

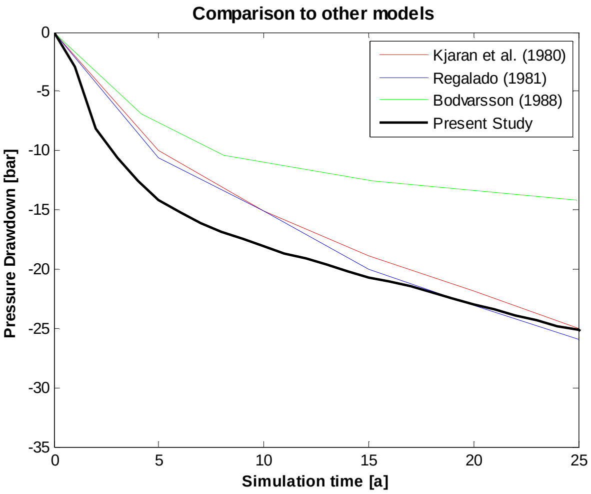

Fig. 7. Comparison of pressure drawdown for a constant production of 200 kg/s for various Svartsengi models (Bodvarsson, 1988).

CONCLUSIONS

A deterministic modeling approach for simulating transient conditions in high temperature geothermal reservoirs has been investigated and improved. This involves a preprocessor which creates necessary input files for the numerical simulator iTOUGH2 with an interactive creation of irregular meshes using Voronoi tessellation. A postprocessor has also been developed which provides a convenient method of importing model results into MATLAB with various graphical interpretation options for the data. By using the postprocessor convective patterns of pore velocities can be illustrated within the reservoir with temperature, pressure or saturation contours in the same graph. It is also possible to compare observations of measured field data to the simulated transient response. The simulator iTOUGH2 is used for optimization of selected parameters, giving information about correlations and estimation quality. An error analysis of the residuals and the estimated parameters provides valuable information about the estimation uncertainty, the adequacy of the model structure, the quality of the data, and the relative importance of individual data points and parameters.

Model validation is performed on data obtained from the Svartsengi geothermal system in SW-Iceland. The validation demonstrates how effective the modeling approach is in simulating the transient physical conditions. The parameter estimation was effective in matching the observed pressure drawdown, temperature and enthalpy of the produced fluid. However, over-parameterization is prone to occur if modeling criterions are not carefully applied when appropriate.

Comparison with other numerical models indicates that models based on different physical assumptions of reservoir characteristics can match the Svartsengi data, but they give different pressure decline predictions. The present study predicts a response similar to the responses of simple analytical models after 25 years of production. However, one should be careful in applying analytical models that only consider pressure diffusion, when in real geothermal systems, both mass and heat flow is important.

Presently, it is not known how detailed a model of a geothermal system must be to possess reasonable predictive capabilities. More complex models of other geothermal systems using a well-by-well approach introduce a greater degree of freedom, but it can be more difficult to obtain solutions. Also, the intrinsic weakness of the more simple volumetric method is the fixed recovery factor, while energy recovery strongly depends on the recharge, physical conditions and properties of the reservoir. Thus, the present modeling approach is a potential alternative to earlier modeling approaches, both simpler and more complex. Its main advantage is that it takes into account the main physical conditions and properties of geothermal resources. This model approach can therefore be used for a future national reassessment of geothermal resources in Iceland.

Further research and development is encouraged to improve the pre- and postprocessors interpolation approach. The modeling approach should also be applied to other geothermal systems. If the overall physical conditions of an unexploited reservoir are approximately known, the uncertainty in its production capacity can be estimated on the basis of various physical property extremes. Using the estimated physical properties of the three well-known high-temperature systems in Iceland, i.e. Svartsengi, Nesjavellir and Krafla, the resulting property extremes can be applied in the analysis of systems with unknown reservoir production response.

ACKNOWLEDGMENTS

This project was supported by the National Energy Authority of Iceland, Iceland GeoSurvey and University of Iceland. Hitaveita Sudurnesja is acknowledged for a well documented production history of the Svartsengi geothermal system, which is used for model validation. In addition, colleagues at Iceland GeoSurvey and Prof. Mike O'Sullivan at University of Auckland in New Zealand inspired some of the ideas presented in this paper.

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