Enhanced Geothermal Reservoir Simulation

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This paper introduces the current state of art in computer modelling of enhanced geothermal system (EGS) and expends our research efforts in high performance simulation of EGS. We include a brief introduction of our integrated geothermal reservoir simulator PANDAS and its applications in: (a) model benchmark, (b) fracture and permeability evaluation based on recorded microseismic events and (c) simulation and evaluation of a certain multiple well EGS. We demonstrate the usefulness and efficiency of our software PANDAS.

Keywords: enhanced geothermal reservoir, simulation, finite element, permeability, HDR/HFR/HWR, microseismicity.

Introduction

A large amount of research and testing on EGS, such as HDR (hot dry rock), HFR (hot fractured rock) and HWR (hot wet rock) geothermal reservoirs, have been accomplished worldwide in the past 30 years including reservoir construction, fluid circulation and heat extraction. A successful EGS reservoir strongly depends on thermal-fluid flow distribution at any given time. This is primarily determined by: (1) the nature of the interconnected network of hydraulic stimulated joints and open fractures (including both stimulated and natural) within the flow-accessible reservoir region; (2) the mean temperature and pressure in the reservoir; (3) the cumulative amount of fluid circulation (reservoir cooling) that has occurred; and (4) water loss (e.g. Brown et al., 1999). In order to understand, model and predict the thermal power performance of an EGS reservoir, it is necessary to have good measures and understanding of the following two interrelated reservoir properties: (a) the effective heat transfer volume at high temperature; and (b) the fracture/joints and its distribution within the effective heat transfer volume. Both highly affects the reservoir characteristics (i.e. permeability), which are complicated and are functions of the applied reservoir pressure/stress that are controlling the nature and degree of interconnection within the network of fractures.

EGS – A THMC coupled system

A literature survey (e.g. Bjornsson and Bodvarsson, 1990) on thermal, hydrological and chemical characteristics of geothermal reservoirs and their relevant parameters - permeability, permeability-thickness, porosity, reservoir temperature and concentration of dissolved solids and non-condensable gases – suggests that reservoir permeability, porosity and total dissolved solids tend to be a function of temperature. Permeability and porosity generally decline with increasing temperature, while the concentration of dissolved solids increases with increasing temperature, reflecting a general increase in mineral solubility. A possible explanation of decreasing permeability with temperature is a local increase in crustal stresses caused by thermoelastic phenomena. Thermal expansion of the reservoir rocks will reduce the number voids and cracks in the rock matrix and hence reduce permeability. Another major factor that affects the permeability is mineral deposition. For example, the solubility of calcite decreases with increasing temperature, causing clogging of pore spaces at high temperatures. All the above demonstrates that an EGS is a complicated Thermal-Hydro-Mechanical-Chemical (THMC) coupled system, which requires more comprehensive understanding and modelling of coupled processes than is commonly done in standard reservoir engineering.

Recent studies on computer modelling

Recent studies on computer modelling the conventional geothermal reservoir engineering and the EGS/HDR system are reviewed by O'Sullivan et al. (2001) and Sanyal et al. (2000) respectively. They show that computer modelling is routinely applied in conventional hydrothermal reservoir engineering, but it is comparatively premature in EGS simulation which still rely much on the EGS expertise and feedback of practical active modellers and engineers. Based on the above and other recent studies, existing simulators are faced with following challenges: (1) Geomechanical deformation/rock stress and its fully coupling with the multiphase thermal-fluid flow and chemicals are not addressed yet. Such coupled models are critical for analysing the geothermal reservoir system especially for EGS. Further research is needed in exploring different approximations for coupled processes with vastly different intrinsic spatial and temporal scales. Such a coupled treatment can potentially provide a more realistic description of geothermal reservoir processes during natural/stimulated evolution as well as during exploitation. It can also provide added constraints that can help reduce the inherent uncertainty of geothermal reservoir models; (2) a reliable fully-coupled treatment of 3D fluid flow and mass transport with detailed chemical interactions between aqueous fluids, gases, and primary mineral assemblages still requires further research. This is currently available in hydrothermal code TOUGH2, but not available in the other codes including all the HDR simulators/FEM simulators; (3) the relevant reservoir model generation and meshing are still difficult and time consuming especially for fracture dominated EGS. The finite differential method is widely used in geothermal modelling but requires regular rectangular mesh structure. The popular geothermal code TOUGH2 may handle irregular meshes theoretically, but most of models set up using TOUGH2 contain some structure, such as layering. It is impossible to explicitly describe the complicated fractures in an EGS reservoir with such mesh structures. Unstructured mesh may be a better choice, but no unstructured mesh based solver-finite element solver- as powerful as such as TOUGH2 is available for geothermal simulation yet; (4) no module for visualizing microseismicity and evaluating the relevant rupture and permeability distribution for the further simulation has been integrated into the simulator so far; (5) No multiscale computing or parallel computing involved in the widely available geothermal simulators yet despite their well-studied and widespread application in other fields.

In conclusion, further computational model and code developments are urgently needed to improve our understanding of geothermal reservoir and the relevant natural and/or enhanced evolution such as of enhanced geothermal reservoir system, and achieve a more accurate and comprehensive representation of reservoir processes in more details, 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 (e.g. O'Sullivan et al., 2001, Sanyal et al., 2000). This presentation will focus on our research efforts towards high performance simulation of enhanced geothermal reservoir systems.

An Integrated Geothermal Reservoir Simulator

PANDAS - Parallel Adaptive static/dynamic Nonlinear Deformation Analysis System - for simulating the coupled geomechanical-fluid flow-thermal systems involving heterogeneously fractured geomaterials is being developed using finite element method (FEM). It addresses the key scientific and technological challenge in developing enhanced geothermal energy. Namely, it is targeting a new predictive modelling capacity spanning different temporal and spatial scales with the potential to yield breakthroughs in understanding how to enhance the flow of water through the enhanced geothermal field and how to sustain it over decades such that the trapped heat energy can be extracted.

Currently, PANDAS includes the following five key components: Pandas/Pre (for visualizing and evaluating microseismic events and the relevant ruptured zone and permeability, mesh generation), ESyS_Crustal (FEM solver for an interacting fault system), Pandas/Thermo (FEM thermal solver), Pandas/Fluid (FEM solver for porous media flow) and Pandas/Post (for visualizing computing results). All the above modules can be used independently or together to simulate individual or coupled phenomena (such as interacting fault dynamics, heat flow and fluid flow) with or without coupling effects. It aims to provide (a) visualization the recorded microseismic events and further evaluation of the fracture location and evolution, geological setting, the reservoir characteristics (e.g. permeability) and mesh generation; (b) a non-linear finite element based numerical solution to model and evaluate a certain geothermal reservoir under various affecting factors. For more details, refer to Xing et al (2002; 2006a; 2006b; 2007; and 2008).

Benchmark and Application Examples

PANDAS has been applied in several different cases. We list a few of examples to show its accuracy, stability, usefulness and efficiency in simulating the enhanced geothermal reservoir system.

Benchmark of computational model

Verification and benchmark testing of our finite element based geothermal code PANDAS are accomplished by comparing the available analytical solutions and/or the widely accepted results with those calculated by PANDAS. So far, the following cases have been tested; only the case 3) is further described here.

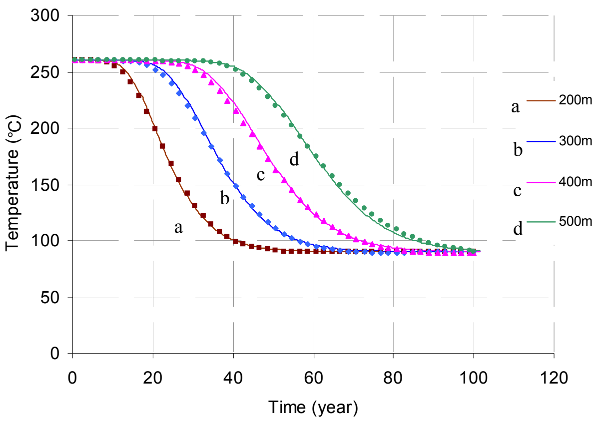

Figure 1: Comparison of FEM result with analytical one (curves) on thermal-fluid flow in fractured rocks. It shows the fluid temperature evolution at different positions of the fractured zone. Around the production well (500m), the temperature remains above 150℃ at 60 years. Assuming an allowable maximum temperature decrease of 40℃ at the projection well, it will last up to 50 years with the injection rate of 0.017litre/s. Refer to Xu et al., (2007) for the detailed model description.

1) Heat transfer/Darcy flow in porous media (analytical solution available)
2) Convection dominated thermal-fluid flow in porous media (analytical solution available)
3) Thermal-fluid flow in fractured rocks (analytical solution available for a single fracture)
4) Two phase thermal-fluid flow in porous media (water and vapour, DOE (Department of Energy, USA) benchmark result).

Fluid flow in most enhanced (HDR/HFR) geothermal reservoirs is dominated by fractures and their distribution, which corresponds to the benchmark case 3). How the fractures affect the heat transfer between the fluid and the rock mass during injection process must be critically addressed. To investigate the advancement of the thermal fluid during the injection process into the fractured reservoir system, PANDAS is verified through comparison with the analytical solution of a simplified reservoir system consisting of a horizontal fracture intersecting an injection well and a production well as detailed in Xu et al. (2007). The analysed zone spans 30m thickness along the vertical direction and is composed of a main horizontal fracture and a permeable rock mass. To be analysed by both the analytical and finite element methods, in which the permeability of the 30m thick (D=15m) fracture zone is taken as 1.0E-30 in FEM simulation (close to zero to compare with the analytical solution). The transmissibility of the main fracture with the aperture H=0.01m down the middle of the fracture zone is 1 Darcy metre; and the temperature of injected fluid is 90℃, the initial temperature of rock matrix is 260℃. Figure 1 shows the benchmark result of two wells with the distance of 500m. The FEM calculation result agrees well with the analytical solution.

Microseismicity and EGS reservoir

Hydraulic stimulation is a basic concept of improving the residual permeability of the in-situ rock mass at depth and still remains the main mechanism to be envisaged for the creation of an enhanced geothermal reservoir (i.e. HDR/HFR/HWR). PANDAS has been developed and applied to visualize the microseismic events, to monitor and determine where and how the underground rupture proceeds during a hydraulic stimulation process, to determine the domain of the ruptured zone and to evaluate the material parameters (i.e. the permeability) for the further numerical analysis. Figure 2 shows the permeability distribution of a geothermal reservoir calculated from the microseismic events recorded during a hydraulic stimulation process. A virtual 8-well geothermal reservoir (i.e. 1 injection well + 7 production wells in a reservoir with the dimensions of Length x Width x Height:

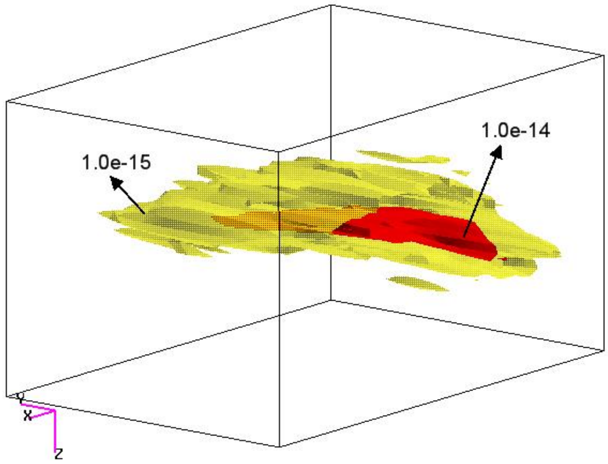

Figure 2: An example of the calculated permeability distribution of a geothermal reservoir thorough the microseismic events recorded during a hydraulic stimulation process.

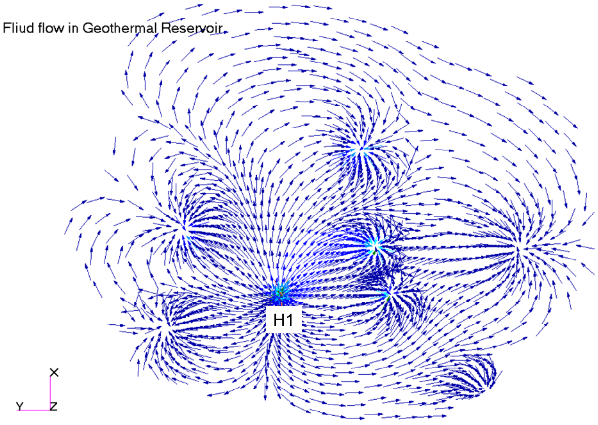

Figure 3: The simulated fluid flow in a certain fractured geothermal reservoir with 7 production wells and 1 injection well H1. It is calculated in 3D but shown in a certain cross-section here.

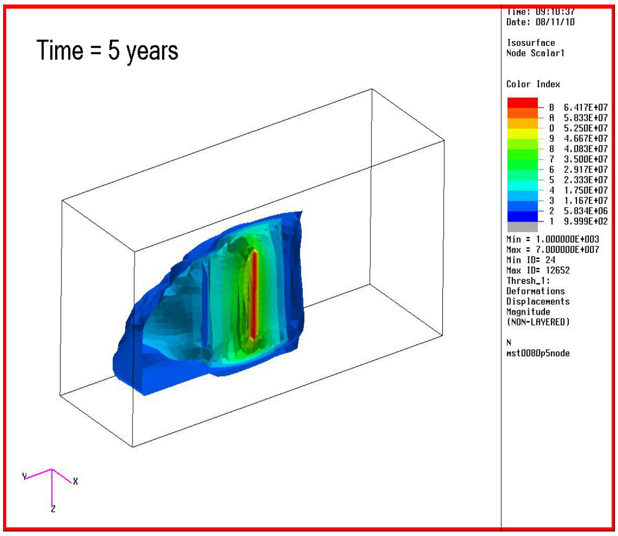

Figure 4: The simulated hydraulic pressure distribution at 5 years in a certain fractured geothermal reservoir with 7 production wells and 1 injection well H1(Figure 3).

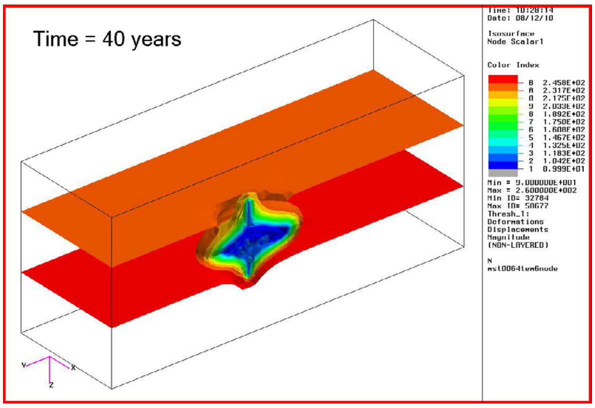

Figure 5: The simulated temperature distribution at 40 years in a certain fractured geothermal reservoir with 7 production wells and 1 injection well H1 (Figure 3)

4000 m x 3000 m x 1750 m) is designed and further analysed using PANDAS. The snapshots of the relevant results are shown in Figures 3, 4 and 5 with one injection well located at H1 (Figure 3).

Summary

We discuss the key improvements required in simulating an enhanced geothermal reservoir system (HDR/HFR/HWR) for further improving our understanding of geothermal reservoir and the relevant natural and/or enhanced evolution such as of EGS based on relevant studies. The goal is to achieve a more accurate and comprehensive representation of reservoir processes in more detail and reduce the uncertainties in models, and enhance the practical utility and reliability of reservoir simulations as a basis for field development and management. Our research in PANDAS towards high performance simulations of enhanced geothermal reservoirs is introduced and then verified using relevant benchmarks. It is further applied in a virtual design and assessment of a multiple well reservoir system based on the permeability distribution calculated from the recorded microseismic events. Both benchmark and application examples demonstrate its accuracy, stability and potential usefulness in simulating the enhanced geothermal reservoir system. PANDAS will be further developed for a multiscale simulation of multiphase dynamic behaviour for a specific geothermal reservoir system. More details and additional application examples will be given during the presentation.

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