Numerical simulation of geothermal reservoir systems with multiphase fluids

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This paper describes a modular framework for simulating geothermal well and reservoir performance. The numerical model is able to account for transient, three-dimensional, single- or two-phase fluid flow in normal heterogeneous or fractured-matrix formations. Both conductive and convective heat flow are accounted for and fluid states in the reservoir can range between liquid phase, two-phase steam-water mixtures to superheated steam. Both short term well reaction and long term reservoir performance can be monitored as dynamic mass/heat flow processes. Equations-of-state (EOS) for water and CO_2 are integrated as part of the fully-coupled nonlinear finite element simulator. In this paper, the code has been applied for use in geotechnical risk assessments for mine developments in geothermal areas. Comparison of EGS-CO_2 and EGS-water is demonstrated in the paper and results show that the simulator PANDAS/ThermoFluid can be used for both conventional geothermal fields and enhanced geothermal systems.

Keywords: Numerical simulation, Enhanced geothermal system, EGS, Geotechnical risk assessment, Carbon dioxide

Introduction

Geothermal energy is regarded as a renewable, clean, cost effective energy source, which is becoming increasingly attractive, especially since the enhanced geothermal system (EGS) has been proposed and applied as a new type of geothermal power technology. Geothermal reservoir modeling has been played an important role as an integral part of reservoir assessment and management in the past few decades. Although computer modeling is routinely applied in hydrothermal reservoir engineering, there are several aspects that continually need improvement:

(1) Two-phase flow phenomenology. This includes the implementation and calibration of relative permeability and capillary pressure, two-phase flow in fractures and mass transfer between phases (evaporation and condensation);

(2) Non-equilibrium models. To relax assumptions of local thermodynamic equilibrium, several non-equilibrium models have been developed, including double porosity models (Warren & Root, 1963), explicit fracture treatment (for sparsely fractured systems) and statistical models ("MINC"-TYPE, Pruess & Narasimhan, 1985) (for densely fractured systems);

(3) Natural-state modeling. Further validation of the computed natural state against early exploration well data is required;

(4) Constitutive representations. Reservoir fluids with dissolved solids (i.e. NaCl) and non-condensable gases are now available in several simulators. Modeling of fluid under extremely high temperature and pressure (supercritical state) is already being conducted but not in the geothermal modeling arena;

(5) Coupled reservoir chemistry. There are a few calculations that have been reported incorporating reactive chemistry, coupled with fluid flow by dissolution and precipitation of solids (creation and destruction of porosity and permeability), however, this area still provides a challenge to geothermal modeling;

(6) Automatic inversion techniques. Inverse modeling uses an iterative inversion procedure to drive conventional forward reservoir models (treated as subroutines). With the increase in model complexity and degrees of freedom, the computational cost is extremely high.

In conclusion, further computational modeling and code development is urgently needed to improve our understanding of geothermal reservoir and the relevant nature. It is also needed for the enhanced evolution such as of enhanced geothermal reservoir system, and achieves a more accurate and comprehensive representation of reservoir processes in more details. It also helps 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. This paper will focus on our research efforts towards the simulation of enhanced geothermal reservoir systems with multiphase fluids.

PANDAS/ThermoFluid

PANDAS (Parallel Adaptive Nonlinear Deformation Analysis Software) is a modular system of finite element method based modules. Currently, it includes the following four key components:

- ESyS_Crustal for the interacting fault system simulation;
- PANDAS/Fluid for simulating the fluid flow in fractured porous media;
- PANDAS/Thermo for the thermal analysis of metals and fractured porous media;

- PANDAS/Pre and PANDAS/Post for conceptual modeling, mesh generation and visualization.

All of the above modules can be used individually or together to simulate phenomena such as interacting fault system dynamics, heat flow and fluid flow with or without coupling effects.

PANDAS/ThermoFluid (the fully coupled modules of PANDAS/Thermo and PANDAS/Fluid) is a finite element method based module for simulating the fluid and heat flow in a fractured porous media by solving the conservation equations of macroscopic properties numerically.

The mass and energy conservation equations for transient two-phase water/steam coupled heat/fluid flow in porous medium used in PANDAS are given in Equations (1) and (2):

$$\begin{aligned}&\frac{\partial}{\partial t}[\phi(S_w\rho_w + S_s\rho_s)] = \\ &\nabla\cdot[\rho_w \frac{\mathbf{K}k_{rw}}{\mu_w}(\nabla P_w - \rho_w g\nabla Z)] + \\ &\nabla\cdot[\rho_s \frac{\mathbf{K}k_{rs}}{\mu_s}(\nabla P_s - \rho_s g\nabla Z)] + q_m\end{aligned} \quad (1)$$

$$\begin{aligned}&\frac{\partial}{\partial t}[\phi(S_w\rho_w u_w + S_s\rho_s u_s) + (1-\phi)\rho_r c_r] = \\ &\nabla\cdot[\rho_w h_w \frac{\mathbf{K}k_{rw}}{\mu_w}(\nabla P_w - \rho_w g\nabla Z)] + \\ &\nabla\cdot[\rho_s h_s \frac{\mathbf{K}k_{rs}}{\mu_s}(\nabla P_s - \rho_s g\nabla Z)] + \nabla\cdot(\lambda\nabla T) + q_e\end{aligned} \quad (2)$$

To complete the governing equations, it is assumed that Darcy's Law applies to the movement of each phase (momentum balance):

$$\mathbf{v}_w = \frac{\mathbf{K}k_{rw}}{\mu_w}(\nabla P_w - \rho_w g\nabla Z) \quad (3)$$

$$\mathbf{v}_s = \frac{\mathbf{K}k_{rs}}{\mu_s}(\nabla P_s - \rho_s g\nabla Z) \quad (4)$$

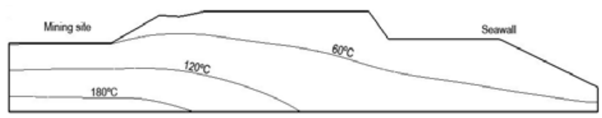
where P is fluid pressure [Pa]; ϕ is the porosity; S is the phase saturation, with S_w+S_s=1; ρ is the density [kg/m^3]; K is the intrinsic permeability tensor of the porous medium [m^2], k_r is the relative permeability of the phase; μ is the dynamic viscosity [kg/m·s]; g is gravity, Z is the depth; u and h are specific internal energy and specific enthalpy respectively [kJ/kg]; λ is the thermal conductivity tensor of the porous medium [W/m·K]; T is temperature [℃]; q_m and q_e are source/sink terms of the total mass and energy respectively [kg/m3·s, kJ/m3·s]; v is the fluid velocity vector in [m/s]; the subscript w, s and r denote water, steam phase and rock matrix respectively.

Thermodynamic properties of reservoir fluids (such as water and CO_2) are of vital importance to understand the subsurface physical-chemical and geological processes. The most accepted IAPWS-95 formulation (Wagner & Prub, 2002) for water equation-of-state (EOS) is integrated in our simulator, which allows us to retrieve basic physical parameters such as density and dynamic viscosity, as well as the saturated properties for phase transition modeling. SWEOS, an EOS for CO_2 which was originally developed by Span and Wagner (1996) based on their algorithm of an empirical representation of the fundamental equation of Helmholtz energy, has also been implemented into our simulator to model EGS-CO_2 processes.

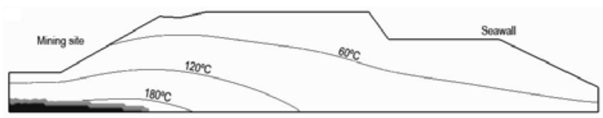
For more details of PANDAS, please refer to Xing & Makinouchi (2002), Xing et al. (2006a, b, 2007, 2008, 2010). Model validation of PANDAS/ ThermoFluid code is reported in Xing et al. (2008, 2009).

PANDAS/ThermoFluid application in Geotechnical risk assessments for mine developments in geothermal areas

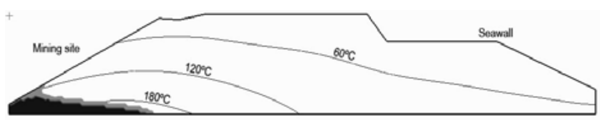
To demonstrate the feasibility and value of multi-phase fluid flow modeling as a pit design tool and for risk analysis of geothermal hazards during mining in hot ground, a numerical model was developed for a gold mine site using the PANDAS/ThermoFluid model code. PANDAS/ThermoFluid was used for simulation of temperature, pressure and steam distribution in the seawall and foundation of the dam along a north-northeast to south-southwest oriented cross section.



(a) Stage 1



(b) Stage 2



(c) Stage 3

Steam Zone Mixed Zone Liquid Water Zone

Figure 1: PANDAS/ThermoFluid results of the cross section model of pit excavation for three development stages.

For demonstration purpose, three pit excavation stages were simulated. The first to a depth of 90m, the second reaching the top of the boiling zone at 180m and the third down to 270m below surface.

It was found that after the first stage of excavation to 90m steam did not develop throughout the model domain despite temperatures computed to be partly significant above 100ºC. This is due to high hydrostatic pressures preventing water from boiling at this stage. The simulation results for the second and third development stages predicted boiling to occur below the pit floor and in the lower benches of the seawall.

Short-term/long-term modeling of fracture dominated EGS-water and EGS-CO_2

Operating enhanced geothermal systems (EGS) with CO_2 instead of water as a heat transmission fluid is a new attractive concept with several benefits including: The lower viscosity of CO_2 would yield larger flow velocities for a given pressure gradient; less power consumption for fluid circulation systems due to buoyancy effects and geologic storage of greenhouse gases as an ancillary benefit (Brown, 2000, Pruess, 2006). The following section demonstrates simulations using EGS-water and EGS-CO_2 under typical geothermal field situations to compare the efficiency and longevity of both systems as well as the estimation amount of geologic storage of CO_2.

Pruess (2006) has compared the thermodynamic properties of CO_2 and water under typical reservoir conditions. A five-spot well pattern geothermal field was modeled by TOUGH2 (Pruess, 2006) and a series of comparisons between EGS-CO_2 and EGS-water has demonstrated the advantages of using EGS-CO_2 such as the long-term performance (up to 36 years) heat exaction rate, mass flow rate and pressure/temperature field.

In the development of enhanced geothermal systems, greater focus is shifted to the short-term dynamic response of well tests. A number of tests (with or without tracers) need to be run between the injection and production wells before power generation to assess the ability of production and circulation within an EGS. Here, a simplified 500x200m fracture dominated geothermal field (Figure 2) is modeled by PANDAS/ThermoFluid to compare both long-term and short-term performance of EGS-CO_2 and EGS-water.

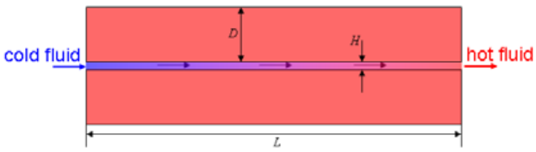


Figure 2: A fracture dominated geothermal field. L=500m, D=100m, H=0.1m. Permeability of the fracture zone is $5\times10^{-14}m^2$. Rock density is $2.65\times10^3 kg/m^3$, specific heat is 1kJ/(kgK), thermal conductivity is 2.1W/(mK). Initial temperature of entire region is 250℃, the Injection fluid is 90 ℃.

Figure 3 shows the fluid velocity evolution at an early stage of the well test. With the same pressure drop between injection well and production well, CO_2 has higher flow rates than water (2.5×10^{-3} m/s for CO_2 to 8.7×10^{-4} m/s for water at its stable stage). It can also be seen that CO_2 takes about 81 hours to reach the stable state, while water takes less than 50 hours. The reason for the longer stabalization time for CO_2 is because it has a larger ratio of fluid density to viscosity (Pruess, 2006) and a larger compressibility (about 8 times of water) than water under reservoir pressure/temperatures.

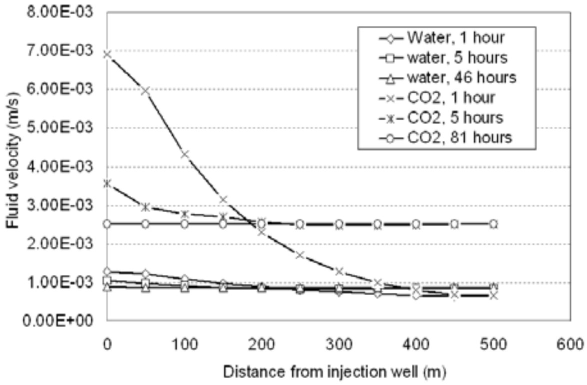


Figure 3: Fluid velocity evolution at early stage of well test. Injection well pressure is 44MPa, constant pressure drop of 10MPa is set between the injection well and production well.

Figure 4 shows a long term temperature distribution along the fracture zone. For this particular case, it takes less than 10 years for EGS-CO_2 to reduce temperature within the entire region to under 200℃, while EGS-water requires more than 20 years before temperature drops to 200℃. This is due to CO_2's higher heat extraction rate which was suggested by Pruess (2006).

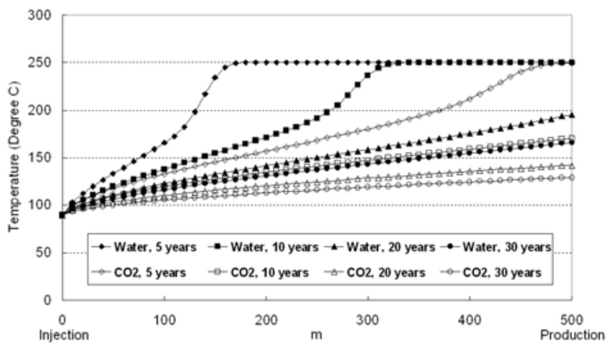


Figure 4: Comparison of fracture zone temperature at different years. Constant pressure drop of 10MPa is set between the injection well and production well. With the fracture space of 100m, flow rate for water and CO_2 are 7.3kg/s and 10.8kg/s, respectively.

Conclusions

Computer modeling of geothermal systems has been widely used in industry. Further computational modeling and code development is urgently needed to improve our understanding of geothermal reservoir and the relevant nature. It is also needed for the enhanced evolution such as of enhanced geothermal reservoir system, and achieves a more accurate and comprehensive representation of reservoir processes in more details. It also helps 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. This paper introduced a simulator 'PANDAS/ThermoFluid' to model the transient, non-isothermal, multiphase fluid flow in heterogeneous or fractured-matrix formations for simulating geothermal well and reservoir performance. It was applied for use in a geotechnical risk assessment of an open pit mining site situated in hot ground. As well as to look at short-term/long-term modeling of fracture dominated enhanced geothermal systems (EGS) with water and CO_2 as heat transmission fluids, PANDAS/ThermoFluid has proven to be a valuable tool to support the development and implementation of geothermal risk management strategies to combat geothermal hazards. Results also show its efficiency and usefulness in simulating both conventional geothermal fields and enhanced geothermal systems with multiphase fluids.

Acknowledgements

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