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Inverting methods for thermal reservoir evaluation of enhanced geothermal system

Gang Liu, Bingjie Zhou, Shengming Liao*

School of Energy Science and Engineering, Central South University, Changsha, Hunan 410083, China

A R T I C L E I N F O

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A B S T R A C T

Enhanced geothermal system (EGS) is considered as a solution for current energy crisis and environmental pollution; however, thermal reservoir of EGS is difficult to be accurately quantified. In reservoir evaluating processes, it is very hard to precise the unknown reservoir parameters. This paper, through reviewing the disadvantages of EGS reservoir evaluation methods and parameters estimation methods in previous studies, found that the reservoir evaluation based on probability model is inaccurate. It is also found that there is less previous studies on resources evaluation by solving inverse problem of heat conduction, while the used methods for solving inverse heat conduction problem (including Tikhonov regularization, Gradient Optimization and Decentralized Fuzzy Inference) have their drawbacks. Then, we proposed a novel fuzzy inversion model for reservoir evaluation. This three-dimensional fuzzy inverting model, including three main strategies of heat transfer direct problem modeling, inverse problem modeling and experimental validation, is built in terms of thermal physical parameters of reservoir. The fuzzy inversion model is able to compute the entire geothermal field temperature, establish the quantitative relationship between heat storage quantity and reservoir thermal property, and evaluate EGS heat reservoir. The proposed framework in this study can be used as a guidance for geothermal researchers and companies to build an evaluation tool of energy resources of EGS.

1. Introduction

An enhanced geothermal system (EGS) is a typical clean energy utilization without emission and waste during the using processes. As shown in Fig. 1, geothermal energy is brought to the ground by medium circulating in injection wells, artificial fracture heat reservoir, and production wells [1]. According to the report *The Future of Geothermal Energy* from the Massachusetts Institute of Technology [2], even 2% of EGS reservoirs developed, it will be able to meet the demand of human energy consumption for long-term. Despite geothermal energy resource abounds in the earth, solid resource investigation and hot dry rock (HDR) evaluation are always crucial premises of utilizing geothermal resource [3]. Therefore, heat reservoir evaluation has practical and long-term strategic significance in the exploration and mining of EGS resource, as all the other renewable energy resources [4].

There are some mature methods of geothermal resource evaluation, like plan fracture method, magma thermal equilibrium method, volume method and numerical analytic method [5,6], but they have many limitations that the reservoir computation formula involves some estimations and theoretical assumptions of uncertainty about the evaluation parameters. As a result, drawbacks and errors are existing in measurement processes. Because of the heterogeneity and anisotropy of heat reservoir medium, the thermal reservoir density, heat capacity, and reference temperature are often roughly regarded as constant (such as averaging). Nevertheless, some important information, such as temperature field, reservoir area, and the thickness of thermal storage can only be extrapolated based on the specific situation, or the results are only to be expressed in the form of probability distribution with the aid of random simulation. Thus, based on present technical conditions, the existing methods are difficult to evaluate geothermal resource accurately [7].

With the demands of national geothermal exploration, a new set of methods for EGS reservoir evaluation has been established by thermal physical parameters of reservoir three-dimensional fuzzy inverting. As shown in Fig. 2, finite measuring points of temperatures in testing well are regarded as observed variables and reservoir parameters, including rock thermal property (such as density, specific heat capacity), location and intensity of heat resource, boundary, and boundary conditions, are regarded as unknown parameters. The fuzzy inference model employs the inversion algorithm to solve these unknown parameters. In this way, the exact reservoir parameters are obtained based on the measuring points of temperatures, and then the accurate temperature field

* Corresponding author.
E-mail address: smliao@csu.edu.cn (S. Liao).

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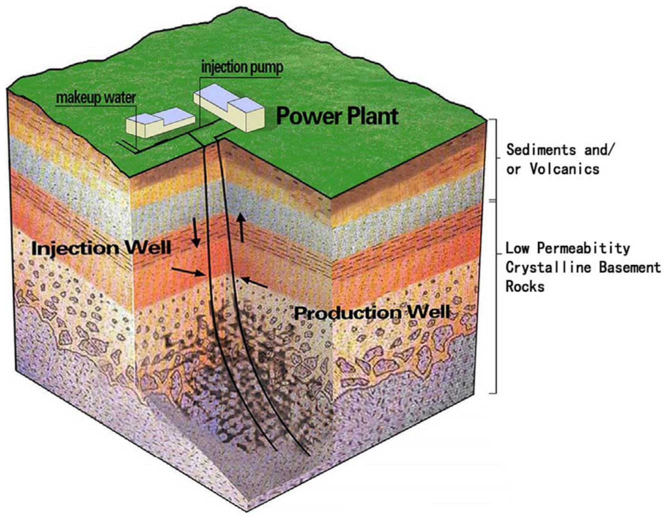

Fig. 1. Diagram of enhanced geothermal system.

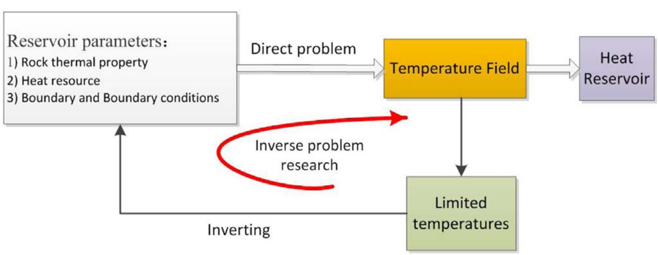

Fig. 2. Propose the basic idea of the project.

distribution is calculated, rather than dependents on the stochastic simulation. The geothermal resource can be evaluated more accurately. Eventually, the problem that objective function convergence excessively relies on the measurement information in gradient optimization method is solved, as well as the reliability and convergence of solution are improved.

This paper reviews the progress of parameters inversion methods and algorithms in EGS reservoir evaluation. It is found that reserves described in probability model is inaccurate, and study on inverse heat conduction method in heat reservoir is absent. Additionally, methods used widely for solving inverse heat conduction problem, including Tikhonov regularization, Gradient Optimization and Decentralized Fuzzy Inference, are flawed. As a result, a new set of novel thermal reservoir evaluation methods based on thermal physical parameters of reservoir three-dimensional fuzzy inverting are presented in this paper.

2. Current research on geothermal reservoir evaluation

2.1. Geothermal parameters estimation of EGS reservoir evaluation

Thermal reservoir is becoming a hot research area in the world wide, with widely concerning on the utilization of geothermal resources. As shown in Fig. 3, the number of published and cited literatures searched in the Web of Science increased rapidly in the past decades. By June 2017, 2857 papers majoring in geothermal reservoir have been researched in Web of Science in the United States, Germany, France, Italy, China. More than 1000 papers have been published before January 2013, which saw rapid increasing of the research interests in EGS reservoir evaluation.

Plenty of studies of EGS resource utilization are from many famous research institutions, including University of California Berkeley (UCB) [8], Swiss Federal Institute of Technology Zurich (ETH) [9], Helmholtz-Centre Potsdam - German Research Centre for Geosciences (GFZ GRCG) [10], French Geological Survey(BRGM) [11], as well as Chinese Academy of Sciences [12–15], Tsinghua University [16], Tianjin University [3], Jilin University [17], and Central South University [18]. All of these researches reveal that the emphasis and difficulty are to evaluate geothermal resources and deal with uncertainty of parameters impacting on temperature filed.

To deal with the uncertainties and randomness in reservoir evaluation processes, a probability model of the heat reservoir has been employed, which is based on statistics analysis in Monte Carlo. In this model, the probably value of reservoir and the calculating results expressed in probabilistic manner are presented after estimating the mean, median, and mode values of uncertainty parameters in heat reservoir. Eventually, the parameter uncertainties is eliminated, and the resource evaluation credibility is promoted, so the Monte Carlo is used widely in a quite long time [19,20].

An important disadvantage of Monte Carlo in evaluation of geothermal fields is its high computational cost, and it is difficult to express the numerical relationship between variables and reserves. Watanabe et al. [21] found that the Sequential Gaussian Simulation, solved by the parallel finite element method (FEM) based on domain decomposition technology, is able to deal with the parameter uncertainties in a long thermal reservoir changing process, with higher calculation efficiency than the Monte Carlo. However, this method demands high accuracy heat reservoir physical model and precise description of the physical properties in reservoir fracture network, such as frequency, size, roughness and distribution, etc. Then, Vogt et al. [22] presented data assimilation with Ensemble Kalman Filter (EnKF), which is used to analyze temperature data from the two existing production wells in French Soultz geothermal field. Compared with the Monte Carlo and the Bayesian Analysis based on gradient analysis, the EnKF is found with larger applicative parameter value scope, less requested data, and better parameter estimation results.

At present, knowledge about reservoir parameters, uncertainties, and indefinite analysis methods of EGS thermal reservoir is not unified and different, even distinct conclusions have been drawn in some studies on stochastic volatility because of the interaction between many random parameters. It is difficult for probability model to express real heat reservoir in only one parameter, so methods based on probability model only express many reservoir results in uncertainties randomly varying in a certain range.

2.2. Thermal reservoir parameters inversion in EGS reservoir evaluation

The direct problem of heat is to predict some results can be observed (such as temperature field), according to heat transfer theories and some relevant conditions. This problem is to solve some mathematical physics equations, in form of second order partial differential equation with constraint conditions. Inverse problem is to determine the characteristic parameters on the basis of measurements and some general principles or models.

To avoid limitations of stochastic analysis in parameters estimating, since the end of last century, inversion methods have been used to study EGS heat reservoir evaluation. Munoz et al. did an experiment to test electricity conductivity in Groβ Schönebeck geothermal test site in Germany [23]. With constraint conditions of the vibration image information and combination with MT inversion method, electricity conductivity is accurately detected to invert thermodynamic parameters. By comparing the Monte Carlo with stochastic inversion technique, Vogt et al. [24] studied possible permeability of heat reservoir and geometries of the simulated zones based on hydraulic connectivity experiment. Zhao et al. [25] analyzed stimulation results and experiment results of EGS lithosphere in Basel, Switzerland by using the Moment Tensor inversion method, reduced calculation time by expressing velocity models in Green's function, and obtained point source solution parameters based on full waveform inversion. The results show that Full Waveform model provides more adaptability than Double