IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

A Review of Multi-field Coupling Simulation of Wellbore and Heat Reservoir in Enhanced Geothermal System

To cite this article: Dandan Shan *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **300** 022076

IOP Conf. Series: Earth and Environmental Science **300** (2019) 022076 doi:10.1088/1755-1315/300/2/022076

A Review of Multi-field Coupling Simulation of Wellbore and Heat Reservoir in Enhanced Geothermal System

Dandan Shan [1, 2], Tie Yan [1, 2, *], Wei Li [1, 2], Shihui Sun [1, 2], Guangdong Lu [1, 2], Huan Zhao [1, 2]

[1] Department of Petroleum Engineering, Northeast Petroleum University, Daqing, China
[2] Key Laboratory of Enhanced Oil Recovery (Northeast Petroleum University), Ministry of Education, Daqing, China

*Corresponding author e-mail: yant@nepu.edu.cn

Abstract. Enhanced geothermal system (EGS) is the most effective mining method for deep dry hot rock resources, and has a broad application prospect. In recent years, it has been widely concerned by all countries around the world. In this paper, the coupling analysis of wellbore and heat storage is carried out. Furthermore the coupling simulation of unsteady heat flow in wellbore and formation, the multi-field coupling simulation of multi-scale heat storage, as well as the multi-field coupling simulation of wellbore and heat storage are deeply analyzed. The research statuses, the positives and negatives, and the future prospects of above model in the application of EGS are described. After summarizing and analyzing the above three research contents, the following suggestions are proposed:(1) Previous research on EGS mainly focuses on the simulation of multi-field coupling in the heat storage, and the heat transfer between the wellbore and the formation is often neglected. Therefore, the coupling between the wellbore and the heat storage should be overall considered, and the flow heat transfer in slender wellbore should be studied. (2) The unsteady heat flow coupling simulation between wellbore and formation did not conduct in intensive study on the wellbore heat transfer of geothermal Wells, the characteristic of geothermal wells is including an aquifer, and the heat transfer in annulus is not involved, the strata should be layered, and considering the heat conduction in annulus, so a more practical heat flow coupling model will be obtained. (3) In order to promote the development of multi-field coupling simulation theory of fractured rock mass, the mechanism of fracture generation and propagation should be deep-going studied to obtain more realistic fracture network distribution patterns.

1. Introduction

The earth is a sphere. It contains rich renewable energy from the earth's core to the earth's crust. According to the record of World Energy Council [1], the total amount of heat stored within 5km of the earth's upper is about 140×106EJ. If the percentile heat quantity is mined, it will provide the world with about 2000 years of energy supply. Geothermal energy usually involves relatively shallow (<3km) resources, and it generally exists in the form of hydrothermal energy. In fact, shallow hydrothermal resources only occupy less than 10% of the total thermal energy. Another form of geothermal energy is found at a considerable depth below the earth's surface. This depth is generally 3-10km and does not contain water. It is called dry hot rock [2].

Compared with hydrothermal heat source, dry hot rock heat source is more common and has higher temperature, so it is more suitable for power generation. In the past few years, the development of dry hot rock is relatively active. Enhanced geothermal system (EGS), as the most effective development technology of dry hot rock resources, has attracted extensive attention in the world [3-6]. The construction of EGS requires hydraulic or chemical irritation to fracture the target hot dry formations. The purpose of that is to improve rock permeability and promote fluid flow.

Compared with the traditional geothermal resources, the EGS has two significant characteristics:the high temperature dry hot rock reservoir is deeply buried, and the reservoir has to undergo artificial fracturing transformation[7]. In order to accurately grasp the heat exchange amount caused by fluid flow in injection and production wells, it is necessary to summarize the current research status in this field and propose the relevant knowledge system needed in the future productivity evaluation of EGS system.

Another important component of the EGS system is the reformed thermal reservoir after fracturing, which is the main environment of system heat recovery. Therefore, it is necessary to clarify the flow heat transfer mechanism of the high-temperature thermal reservoir. In recent years, the shift has also begun to be used to assess the productivity of dry hot rock systems. It not only plays a guiding role in the development of geothermal energy but also provides an important theoretical basis for the exploitation of other unconventional oil and gas resources (Coalbed Gas;Shale Gas;Combustible Ice;etc.) in low permeability reservoirs[8].The establishment of seepage and heat transfer model of fractured rock mass system is conductive to a deeper understanding of dry hot rock reservoir, thus providing theoretical support for the study of thermal reservoir of EGS system.

EGS is a circulation system composed of injection and production well, thermal storage and formation. Each part of the circulatory system plays a decisive role in the continuous and efficient operation of the entire system. In the past, the study of the system is being on the flow and heat transfer of wellbore and heat storage circulation channel, the THM multi-field coupling effect of fractured rock mass in high temperature thermal reservoir, or the THM coupling of wellbore and thermal reservoir considering the inner well section of thermal reservoir. These studies are limited in some sense, and they cannot simulate the running process of EGS system as a whole. To study the flow and heat transfer process of wellbore and heat storage circulation channel is taking the heat storage as equivalent porous medium, yet the fracture part closer to the real situation is not reflected. The direct study of the multi-field coupling in the heat storage shows that although the existence of the fracture is truly reflected but only partially considering the temperature change and the flow condition. There is no way to know about the fluid temperature and flow rate when flowing in and out of the hot reservoir. It can only be given by assumption. For the study on the coupling of wellbore and heat reservoir considering the inner well section of the heat reservoir, it not only considers the flow heat transfer in the wellbore, but also considers the seepage heat transfer in the heat reservoir. However, it will only reflects the local part of the heat reservoir but ignores the heat transfer process between the slender wellbore and the formation outside the heat reservoir. Although the above research results cannot reproduce the overall operation process of EGS, they are involved in all local problems of the circulation system. Therefore, it is of practical guiding significance to carry out analysis on the flow heat transfer law of the coupling between wellbore and heat storage based on the status quo at home and abroad in the above fields.The following part will be divided into three parts to summarize and forecast the research status of this problem:(1)Unsteady Heat Flow Coupling Simulation of Wellbore and Formation;(2)Multi-Field Coupling Simulation of Multi-Scale Heat Storage;(3)Multi-Field Coupling Simulation of Wellbore and Heat Storage.

2. Unsteady Heat Flow Coupling Simulation of Wellbore and Formation

In order to explore the heat transfer process between the wellbore and surrounding strata, it is necessary to understand the well body structure of geothermal wells firstly. The well body structure of geothermal wells in sandstone reservoirs is shown in figure 1. Conventional oil and gas wells are lower tubing below the dynamic liquid level, but the geothermal well is different. The electric submersible pump and pump pipe are only putted into the pump chamber. Due to the limited depth of the pump pipe, the contact area between the fluid and the wellbore in the water production process is large, and the heat dissipation area is larger than that of conventional oil and gas wells.

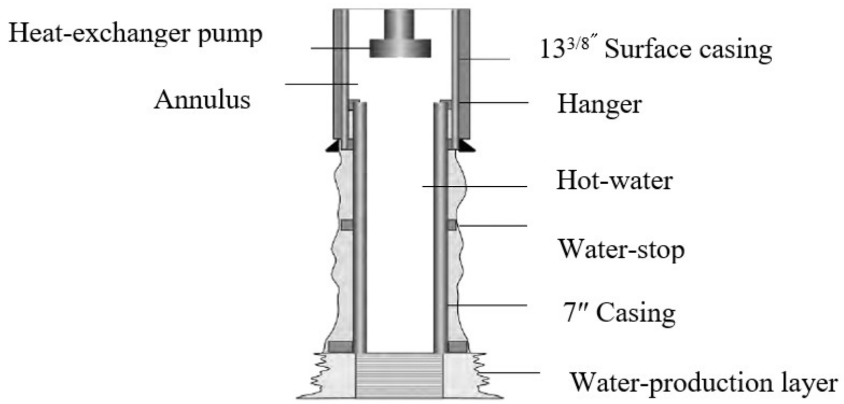

Figure 1. Schematic Diagram of Geothermal Well Structure in Sandstone Reservoir

Based on previous research results, the coupling research methods of wellbore flow and formation heat transfer can be divided into two categories:mathematical model and numerical analysis. Since 1960s, the wellbore heat flow model has been developed rapidly. In 1962, Ramey (1962) [9] proposed a heat transfer model for hot water injection wells. He believes that heat transfer in the wellbore is a steady state and that heat transfer in the formation is a transient radial heat conduction. Willhite (1967) [10]and Willhite et al. (1967) [11] solved the calculation problem between formation and wellbore, and the common solution of wellbore heat transfer coefficient is given. In 1972, Witterholt and Tixier (1972) [12] used the Ramey model to study the effect of heat flow velocity on temperature distribution in wellbore, and the heat flow volume of each layer was analyzed qualitatively. Since then, model research has turned to complex models based on various factors. In 1980, Shiu and Beggs[13] proposed a method model for estimating relaxation parameter A of Ramey model. In 1996, Kabir et al. [14] studied wellbore temperature distribution in both positive circulation and reverse circulation of drilling fluid, introduced transient formation temperature distribution function into TD model, and obtained analytical solution by simple mathematical transformation. In addition to the wide application of mathematical models, numerical analysis is also gradually growing. In 1973, Keller et al. (1973) [15] established a mathematical model of circling temperature in the wellbores with 1D inside, and 2D in the formation, ignoring the radial heat transfer of the drilling fluid, and resolved it using the Finite Difference Method (FDM). In 1982, Marshall and Bentsen (1982) [16] established a model similar to Keller et al. focusing on the stability and speed of finite difference algorithm. Basing on the heat transfer mechanism of a series of media and porous media, Shi et al. (2006) [17] established a two-dimensional temperature distribution model in the wellbore, and the finite difference method is used to simulate the temperature distribution of multi-reservoir oil wells at different radial positions.

The above literature represents the development of this field. They promote the study of heat transfer in and around wellbore. However, there are still several limitations that need to be improved:(1) The study of heat transfer in wells is mostly based on oil and gas wells. (2) The formation temperature before drilling is usually estimated by a linear mean geothermal gradient. (3) The study of heat transfer in surrounding strata is very weak, and it is difficult to use the analytical solution to consider the heat conduction and peace flow in the aquifer. (4) The research on heat transfer between tubing and casing annulus is not complete. In fact, the annular space is a key part of reducing heat loss.

3. Multi-Field Coupling Simulation of Multi-Scale Heat Storage

The study of fractured rock mass system should be considered from different scales, which can be divided into two kinds:macro-scale and micro-scale. The existing research has simplified the macro-scale fractured rock mass system into a single fracture model, a parallel fracture group model and an equivalent porous medium model, while the micro-scale study is mainly reduced to a discrete fracture network model. The multi-scale heat reservoir concept model is shown in figure 2.

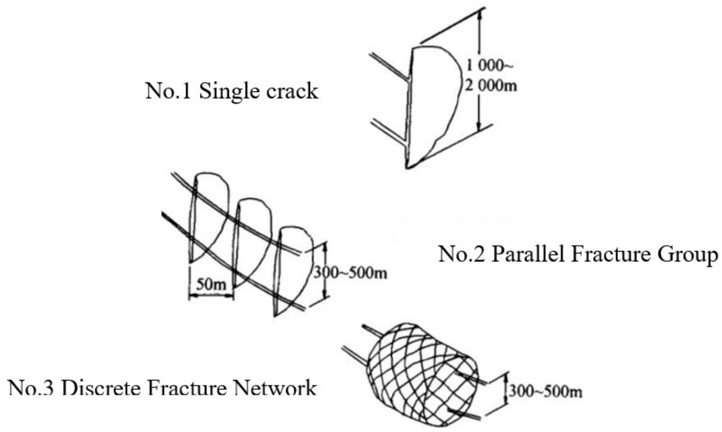

Figure 2. Multi-Scale Thermal Storage Conceptual Model

The most widely used method for the mathematical model of a single crack is the cubic law. Many scholars try to verify this law by means of experiments, but the actual rock fracture surface is often rough and uneven, and the fracture opening will change with the change of stress, so that the water flow is no longer a simple laminar flow state. This leads to the failure of cubic law, so more scholars have proposed various modified models. Since it is difficult to directly measure the mechanical opening of a crack, the equivalent hydraulic opening of the crack is usually calculated based on the water conductivity of the crack. Witherspoon et al. (1979) [18] proposed the relationship between mechanical opening and hydraulic opening. By recording the maximum slit width, counting the typical slit width and width frequency distribution function, the modified equivalent crack width is obtained. Basing on the results of normal seepage test and shear seepage test, Barton (1982) [19] established the relationship between hydraulic and mechanical openness by using joint roughness coefficient. Domestic studies on the coupling of seepage and heat transfer in a single fracture are also abundant. In order to deeply study the heat transfer process between fractured water and bedrock, Chen X Z et al. [20] introduced the boundary layer theory in fluid mechanics to analyze the seepage and heat transfer process of a single fracture surface. Xiong X B et al. [21] summarized the research progress of seepage flow in a single fracture, including the law of fluid migration in the fracture and the different factors affecting the seepage capacity. Zhao J [22] carried out the experiments on seepage and heat transfer characteristics of artificially fractured granite to study the influence of rock mass temperature and fluid velocity. On the premise of comprehensive consideration of heat convection, heat conduction and heat radiation, Zhou Z F et al. [23] obtained the mathematical model of water-heat exchange between rock mass skeleton and water, and on this basis simulated the temperature field of groundwater in rivers.

The complex fracture morphology is difficult to be obtained visually with the naked eye, and it is time-consuming and labor-consuming. In order to simplify the research, many scholars have adopted the equivalent porous medium model to study the mechanism of heat storage seepage and heat transfer. In other words, the fracture network is equivalent to a single pore continuous model with the same permeability and heat transfer performance. The scholar who first proposed this model was Bear [24]. He built the model based on the concept of representing unit volume and regarded fractured rock mass as a continuous medium. Because the model has few parameters and simple expressions, it is often used in seepage problems. However, Neuman et al. [25] had carried out field hydraulic experiments on different scales, but found that it is difficult to find the scale of fractured rock mass which can make the concept of unit volume valid. In order to study the coupling of multiple physical fields, many people have improved and developed the single-pore continuum model. Shaik et al. [26] analyzed the heat transfer process in the natural fracture geothermal field by the energy balance equation considering the water-rock heat transfer effect, but the important parameters were not given. Basing on the energy balance equation, Rutqvist[27]proposed a THM three-field coupling model of gas-liquid two-phase flow considering the stress and deformation of bedrock under the condition of water and rock was in the same temperature, and the finite element program was developed.

The discrete fracture network model emphasizes the contribution of each fracture, and holds that the fluid only flows in the fracture and the bedrock is of low permeability. This model can fully consider the distribution of the fracture, so it can better simulate the seepage and heat transfer of the fracture, which is closer to the real situation. The model contains all the information about the fracture, such as the geometry of each fracture, whether it is connected to the surrounding fracture, and the permeability of the fracture. Long et al. [28] were the first to study this method, they calculated the equivalent permeability tensor through the generated fracture network submodel. Since then, many people had studied the permeability of the system by aiming at the geometric distribution of cracks, such as Bour et al. [29]. Sometimes, the fractal and percolation theory are used to solve the corresponding problems. The fracture network model generally has such characteristic that the thickness direction is very small compared with the other two directions, so the low-dimensional element is generally used to simplify the description. In the study of seepage and heat transfer, the heat exchange between crack and bedrock must be considered, that is the exchange between crack unit and solid unit. In response to this problem, Berkowitz et al. [30] proposed a solution, and Martin [31] promoted it on the previous basis.

The existing research on the seepage and heat transfer law of high-temperature hot-heat storage mostly adopts macro-scale to simulate the fracture distribution, and it is assumed that the fractured rock mass is a single fracture model, a parallel plate fracture model or an equivalent porous medium model. These flow and heat transfer processes in macro-scale fracture are quite different from those in real strata. Therefore, many scholars began to pay attention to the use of fracture network models to simulate the characteristics of dry hot rock reservoirs in recent years, such as Chen B G and Sun Z X et al. On the basis of the previous results, how to get a fracture network model which is more consistent with the real formation characteristics will be the focus of our next research.

4. Multi-Field Coupling Simulation of Wellbore and Heat Storage

The study of EGS thermal energy extraction efficiency and system life is related to the simulation process of multi-physical field coupling under the coupling of wellbore and heat storage. It includes the heat transfer process between the fluid flow in the wellbore and the surrounding strata, and the process of seepage and heat transfer in heat storage at multi-scale. The integrated flow and heat transfer coupling simulation of wellbore and heat storage is the only way to accurately evaluate the productivity and life of the system. The EGS conceptual model for wellbore and heat storage coupling is shown in figure 3.

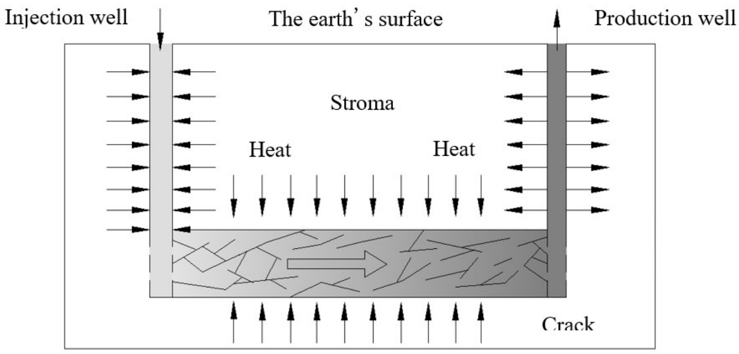

Figure 3. EGS Conceptual Model Diagram for Wellbores and Heat Storage Coupling

In the study of thermal mining performance of EGS system, many people have developed the equivalent porous media model with single porosity. Jiang F M et al. [32] established a three-dimensional transient model of the EGS THM coupling process, and the geothermal reservoir was regarded as an equivalent porous medium with a single porosity. Zeng Y C et al. (2013) [33] extracted the geological data of DP23-1 well and studied the thermal potential of dry hot rock reservoirs. In which the fractured reservoir was regarded as the equivalent porous medium with single pore, and the water circulation process in two horizontal wells was considered. Cao W J et al. (2015) [34] simulated the thermal recovery capacity of EGS with an ideal vertical well model which based on the assumption of local non-thermal equilibrium. The heat storage is also replaced by porous media, ignoring the existence of cracks. The above model applied to the evaluation of thermal recovery capacity is too simplified to truly reflect the actual situation of the formation, and the multi-physical field and multi-scale effect in EGS operation have not been taken into account. Rinaldi et al [35]. carried out the THM coupling simulation for the EGS project, and analyzed the possibility of inducing artificial fractures and natural fractures by using the TOUGH-FLAC simulation simulator. Yao J et al. [36] coupled the wellbore and heat storage in discrete fracture network, and simulated the coupling of THM multi-physical field at the same time. In the process of simulation, the local non-thermal equilibrium equation is considered, and the Desert Peak project is numerically simulated with the random generated fracture model. The thermal production performance and economic prospect of the EGS system are evaluated. However, only the wellbore flow and heat transfer in the fracture are taken into account, but the wellbore heat loss is not involved in the formation with a depth of several thousand meters. In the following research work, it is necessary to deeply study the wellbore-formation flow heat transfer, and coupling with the fracture network heat storage model, in order to fully understand the coupling effect of underground multi-physical fields in the EGS system. This will promote the development of dry hot rock and provide a reliable basis for large-scale commercial mining.

5. Conclusions and prospects

EGS contains two important components: wellbore and heat storage. The study of the process of mass transfer and heat transfer between wellbore, heat storage and bedrock has an immeasurable effect on system evaluation and productivity prediction. While the wellbore has a macro-slender scale, its depth is usually over a few thousand meters. The scale of the heat storage is divided into different grades according to the different objects studied, and the scale closer to the actual scale is the micro-fracture network heat storage. Therefore, the coupling simulation of wellbore and heat storage belongs to the category of multi-scale research. At present, the literature of coupling on wellbore and heat storage is still rare. It is necessary to study the coupled heat flow simulation of enhanced geothermal system considering wellbore and formation heat transfer in order to promote the deep geothermal development research.

The study on heat transfer between geothermal wellbore and formation should be different from that of conventional oil and gas wells. Its characteristic lies in the containing of water layer, the heat transfer study of aquifer is also unclear. Moreover, it ignores the annular internal heat loss, the study of the two parts of heat transfer is also the direction of future efforts.

The real fracture distribution pattern in the thermal storage can not be directly obtained, most of which are only the slit network randomly generated according to the statistical data, and the two-dimensional fracture model is the main. This is mainly due to the three-dimensional fracture network model will increase the amount of calculation, resulting in the computer system operation efficiency is reduced. In order to ensure the accuracy and efficiency, it is necessary to simplify the real three-dimensional fracture network system to obtain a reduced three-dimensional fracture network model to more reasonably and accurately simulate the real EGS thermal storage and fracture system.

Multi-field coupling simulation of wellbore and heat storage based on EGS conceptual model involves many complex engineering problems. In the future, according to the engineering needs, more consideration should be given to the study on the mechanism and simulation of multi-field coupling in the special environment, such as mechanical field and chemical field, and gradually go deep into the three-dimensional THM coupling simulation. This is helpful to better understand the mechanism of EGS accumulation and to evaluate the potential of EGS resources more reasonably and accurately.

Acknowledgments
This work was financially supported by Study on Multi-Field Coupling Simulation of Multi-Scale Heat Storage and Wellbore (No. 2018YDL-10).

References
[1] World Energy Council. Survey of energy resources. Houston, USA:World Energy Council; 1998.
[2] Tester JW, Anderson BJ, Batchelor AS, Blackwell DD, DiPippo R, Drake EM, et al. The future of geothermal energy, impact of enhanced geothermal systems(EGS) on the United States in the 21st Century. Assessment by an MIT-ledinterdisciplinary panel (J.W. Tester, Chairman);2006.
[3] Bertani R. Geothermal power generation in the world 2005e2010 update report. Geothermics 2012;41:1-29.
[4] Genter A, Evans K, Cuenot N, Fritsch D, Sanjuan B. Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS). Comptes Rendus Geosci 2010;342(7):502-516.
[5] Tenma N, Yamaguchi T, Zyvoloski G. The Hijiori hot dry rock test site, Japan:evaluation and optimization of heat extraction from a two-layered reservoir.Geothermics 2008;37:19-52.
[6] Goldstein B A, Hill A J, Long A, Budd A R, Holgate F, Malavazos M. Hot rock geothermal energy plays in Australia. In:Proceedings of the 34th workshop on geothermal reservoir engineering. Stanford, California:Stanford Univer-sity;2009.
[7] ZHU Jialing, HUANG Xiaoxue, Li Jun. A review of wellbore simulation in Enhanced Geothermal System, Chinese Science and Technology Papers Online:http://www.paper.edu.cn.
[8] ZHAO Yangsheng. Multi-Field Coupling of Porous Media and Its Engineering Response[M]. Beijing:Science Press, 2010.
[9] Ramey H J. Wellbore heat transmission[J]. Journal of Petroleum Technology, 1962, 14(4):427-435.
[10] Willhite G P. Overall heat transfer coefficients in steam and hot water injection wells[J]. Journal of Petroleum Technology, 1967, 19(5):607-615.
[11] Willhite G P, Wilson J H, Martin W L. Use of an insulating fluid for casing protection during steam injection[J]. Journal of Petroleum Technology, 1967, 19(11):1453-1456.
[12] Witterholt E J, Tixier M P. Temperature logging in injection wells[C]//SPE Annual Fall Meeting, 1972, San Antonio:8-11.
[13] Shiu K C, Beggs H D. Predicting temperature in flowing oil wells[J]. Journal of Energy Resources Technology, 1980, 3:2-11.
[14] Kabir C S, Hasan A R, Kouba G E, et al. Determining circulating fluid temperature in drilling , workover, and well control operations[J]. SPE Drilling＆Completion, 1996, 11(2):74-79.
[15] Keller H H, Couch E J, Berry P M. Temperature distribution in circulating mud columns[J]. SPE Journal, 1973, 13(1):23-30.
[16] Marshall D W, Bentsen R G. A computer model to determine the temperature distributions in a wellbore[J]. Journal of Canadian Petroleum Technology, 1982, 21(1):63-75.
[17] SHI Ying, SONG Yanjie, XING Libo. Radial temperature distribution in production oil wells[J]. Journal of Daqing Petroleum Instit ute, 2006, 30 (1) :10-11.
[18] Witherspoon P A, Amick C H, Gale J E. Observations of potential size effect in experimental determination of hydraulic properties of fractures[J].Water Resources Research, 1979, 15(5):1142-1146.
[19] Barton N. Modelling rock joint behaviour from in-situ block tests:implications for nuclear waste repository design[R].Columbus:Office of Nuclear Waste Isolation, 1982.
[20] CHEN Xingzhou, LI Baoguo, Dong Yuan, et al. Analysis of water-rock heat transfer in fractured

IOP Conf. Series: Earth and Environmental Science **300** (2019) 022076 doi:10.1088/1755-1315/300/2/022076

rock mass[J]. Northwest hydropower, 2007(3):18-20.
[21] XIONG Xiangbin, ZHANG Chuhan, WANG Enzhi. A review of steady state seepage in a single fracture of rock [J]. Chinese Journal of Rock Mechanics and Engineering, 2009, 28 (9) :1839-1847.
[22] ZHAO Jian. Experimental study of flow-rock heat transfer in rock fractures[J].Chinese Journal of Rock Mechanics and Engineering, 1999, 18 (2) :119-123.
[23] ZHOU Zhifang, WANG Jinguo. Hydrodynamic principle of fracture medium[M]. Higher Education Press, 2007.
[24] Bear J. Dynamics of fluids in porous media[J].American Elseuier, 1972.
[25] Neuman S P, Di Federico V. Multifaceted nature of hydrogeologic scaling and its interpretation[J].Reviews of Geophysics, 2003, 41(3):1014.
[26] Shaik A R, Rahman S S, Tran N H, et al. Numerical simulation of Fluid-Rock coupling heat transfer in naturally fractured geothermal system[J]. Applied Thermal Engineering, 2011, 31(10):1600-1606.
[27] Rutqvist J, Börgesson L, Chijimatsu M, et al. Thermohydromechanics of partially saturated geological media:governing equations and formulation of four finite element models[J]. International journal of rock mechanics and mining sciences, 2001, 38(1):105-127.
[28] Long J C S, Remer J S, Wilson C R, et al. Porous media equivalents for networks of discontinuous fractures[J]. Water Resources Research, 1982, 18(3): 645-658.
[29] Bour O, Davy P. On the connectivity of three-dimensional fault networks[J].Water Resources Research, 1998, 34(10):2611-2622.
[30] Berkowitz B, Bear J, Braester C. Continuum models for contaminant transport in fractured porous formations[J]. Water Resources Research, 1988, 24(8): 1225-1236.
[31] Martin V, Jaffré J, Roberts J E. Modeling fractures and barriers as interfaces for flow in porous media[J]. SIAM Journal on Scientific Computing, 2005, 26(5):1667-1691.
[32] Jiang F M, Chen J L, Huang W B, Luo L. A three-dimensional transient model for EGS subsurface thermo-hydraulic process. Energy, 2014;72(7):300-310.
[33] Zeng Y C; Su Z; Wu N Y. Numerical simulation of heat production potential from hot dry rock by water circulating through two horizontal wells at Desert Peak geothermal field. Energy, 2013, 56, 92–107.
[34] Cao W J, Huang W B, Jiang F M. The thermal-hydraulic-mechanical coupling effects on heat extraction of enhanced geothermal systems[J]. Adv. New Renew. Energy, 2015, 3, 444–451.
[35] Rinaldi A P, Rutqvist J, Sonnenthal E L, Cladouhos T T. Coupled THM modeling of hydroshearing stimulation in tight fractured volcanic rock. Transp. Porous Media, 2015, 108, 131–150.
[36] Yao J, Zhang X, Sun Z X, et al. Numerical simulation of the heat extraction in 3D-EGS with thermal-hydraulic-mechanical coupling method based on discrete fractures model[J]. Geothermics, 2018, 74, 19-34.