Geothermics 73 (2018) 1–15

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Feasibility study of developing a geothermal heating system in naturally fractured formations: Reservoir hydraulic properties determination and heat production forecast

Zheng-Wei Li[a,*], Xia-Ting Feng[a], Yan-Jun Zhang[b,c], Tian-Fu Xu[c]

[a] Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, Shenyang 110819, China
[b] College of Construction Engineering, Jilin University, Changchun 130026, China
[c] Key Lab of Groundwater Resource and Environment Ministry of Education, Jilin University, Changchun 130026, China

ARTICLE INFO

Keywords:
Geothermal heating system
Hot dry rock
Stochastic fracture network
Numerical simulation
Heat production

ABSTRACT

The feasibility of developing a geothermal heating system in naturally fractured formations of northern Songliao Basin was investigated. The flow conductivity of reservoir natural fractures was analyzed based on fracture orientations and present stress regimes. A 2D discrete fracture network model was established based on the field geological data and Monte Carlo simulation method. The hydraulic properties of the geothermal reservoir were calculated using a self-developed MATLAB code, which is programmed based on graph-theoretic flow network and hydrologic balance theory. The equivalent permeability of the DFN model, representative elementary volume (REV), and permeability tensor were studied based on the model. Finally, the heat production performance of the geothermal reservoir was numerically investigated. Research results show that the production temperature maintains at a stable level during 30 years of heat production. The system shows high energy efficiency due to the low energy consumption of the injection and production pumps. Research results in this work can provide preliminary understanding of hydraulic property and heat production of geothermal reservoir in the research area. The research methodology can also be applied in the analysis of other geothermal reservoirs.

1. Introduction

Geothermal energy is attracting increasing attention worldwide due to the urgent demands for renewable and clean energy resources. Besides, geothermal energy is one of the few renewable energy resources that can provide 24-h-a-day power because of its continual stability and wide spatial distribution (Tester et al., 2006). An estimation of the installed thermal power for direct utilization at the end of 2014 equals 70,885 MW, 46.2% increase over the 2010 data (Lund and Boyd, 2016).

In recent years, haze threat has seriously affected the living environment as well as the physical and mental health of people in China. Developing geothermal energy is considered to be an effective way to solve this problem (Liu et al., 2015; Liu et al., 2016). Statistic results show that installed thermal power for direct utilization equals 3687 MW at the end of 2010 in China (Pang et al., 2012). Heating area of geothermal heat pumps have increased from 7.67 million m^2 in 2004, to 100.7 million m^2 in 2009, to 330 million m^2 in 2014 (Lund and Boyd, 2016). In January 2017, a public document regarding the 13th Five Year Plan of the geothermal energy development was released by the National Development and Reform Commission, Ministry of Land and Resources, and National Energy Administration in China. In the outline, a total amount of 260 billion RMB (nearly 40 billion US dollar) will be invested in the development of geothermal energy in the next 5 years (National Report, 2017).

Geothermal energy has long been used for heating. The earliest known commercial geothermal district heating system was built in Chaudes Aigues Cantal, France in the 14th century (Bloomquist, 2003). The most common utilization modes of geothermal energy for heating can be divided into two categories based on the resource type: The direct utilization of hydrothermal resources and the utilization of shallow geothermal resources through a ground source heat pump (Zheng et al., 2012). The spatial distribution of hydrothermal resources is highly inconsistent, which seriously affected the promotion and application of geothermal district heating techniques. Meanwhile, the success rate of geothermal exploration is very low due to the high unpredictability of groundwater circulation characteristics. For ground source heat pump, the insufficient heat recharge is a large obstacle in the stable and long-term operation in severe cold region (Omer, 2008).

Recently, a novel geothermal district heating method, namely,

* Corresponding author.
E-mail address: lizhengwei@mail.neu.edu.cn (Z.-W. Li).

https://doi.org/10.1016/j.geothermics.2018.01.002
Received 19 September 2017; Received in revised form 13 December 2017; Accepted 10 January 2018
Available online 03 February 2018
0375-6505/

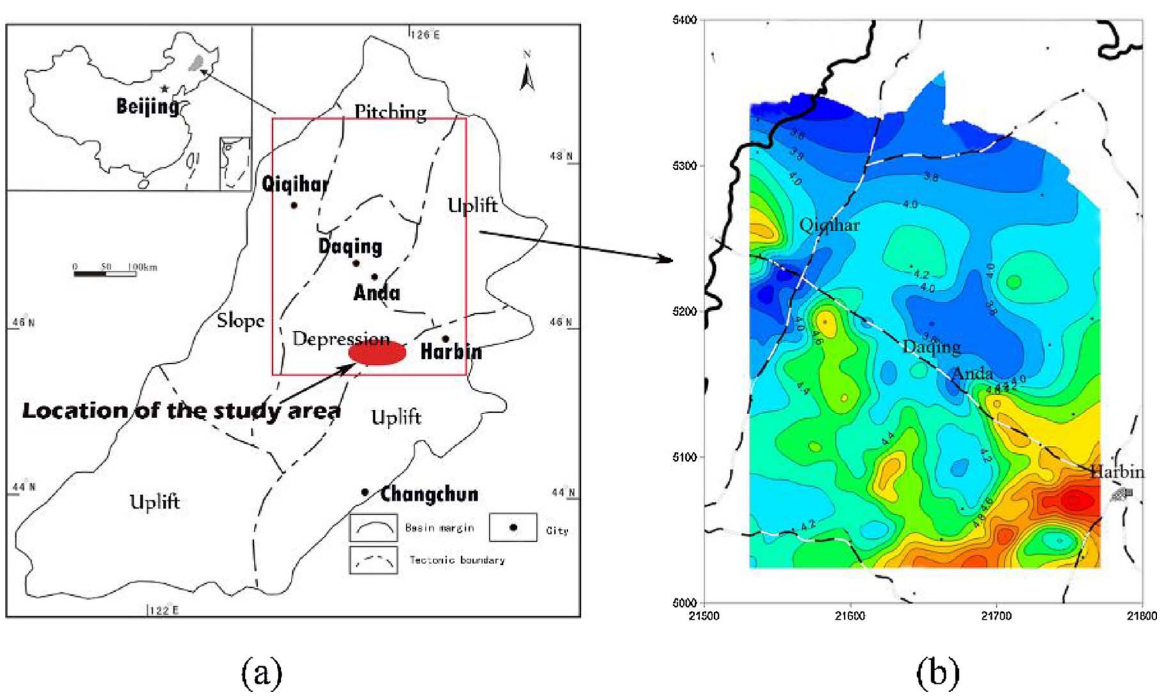
Nomenclature

a	Lower bound of truncated power-law distribution
b	Upper bound of truncated power-law distribution
g	Gravitational acceleration, 9.8 m/s^2
h_1	Depth of the injection well, m
h_2	Depth of the production well, m
h_{inj}	Injection specific enthalpy, kJ/kg
h_{pro}	Production specific enthalpy, kJ/kg
I_R	System flow impedance, MPa/(kg/s)
$K_g(\alpha)$	Permeability calculated from DFN model, m^2
K_{xx},K_{yy},K_{xy}	Permeability components, m^2
$\overline{k_{ij}}(\alpha)$	Mean permeability value obtained from permeability ellipse, m^2
K_1, K_2	Major and minor principle permeability, m^2
n	Sample quantity
P_1, P_2	Constant hydraulic head boundaries
P_{inj}	Bottomhole pressure of the injection well, MPa
P_{pro}	Bottomhole pressure of the production well, MPa
q	Production mass flow rate, kg/s
Q_x, Q_y	Flow quantity in horizontal and vertical directions
R, R_i, R_{i+1}	Pseudo-random numbers
RMS	Root mean square error
W_h	Heat production power, MW
W_p	Power of injection and production pumps, MW
α	Power-law exponent
η	System energy efficiency
η_p	Pump effiency
θ	Angle between the direction of major principle permeability and the positive direction of x axis
μ	Expectation value of normal distribution
ρ	Water density, kg/m^3
σ^2	Variance value of normal distribution

enhanced geothermal heating system (EGHS) has been proposed (Zhang et al., 2015). This method applies the reservoir stimulation and heat extraction techniques of enhanced geothermal system (EGS) to relatively shallow layers containing thermal resources. The Rittershoffen geothermal field located in Bas-Rhin, France is the first EGS field dedicated to heat production. This field is also one of the very few European EGS which is currently under development. The doublet system was designed to be located at a depth of 2.5–3.0 km. The heat extraction rate for this system is expected to be 25 MW (KIT, 2013). Zhang et al. (2015) numerically investigated the feasibility of using enhanced geothermal system correlation techniques (hydraulic fracturing and heat extraction) to develop medium–low temperature geothermal resources for heating purposes in a tight sandstone reservoir in northeast China. The numerical simulation results show that the production mass flow rate is too small, and the thermal breakthrough happens too fast.

In recent years, some demonstration EGS power plant has been built worldwide, with Soultz EGS project in France being the most famous (Hooijkaas et al., 2006). The valuable experience gained from these demonstration projects indicates that a certain degree of natural fracture development is one of the essential conditions of a successful HDR project. The orientation of the natural fractures should be conducive to fluid flow in the present stress regimes (Hickman and Davatzes, 2010).

To reasonably evaluate the heat production performance of a geothermal reservoir, reservoir modeling is crucial. Numerical modeling of naturally fractured formations includes two major methods, discrete fracture network (DFN) model and continuum medium model (Ouenes and Hartley, 2000). As one of the basic works for the establishment of a DFN model, fracture development information in the target formations needs to be detected. Traditional fracture detection methods mainly include conventional logging, well testing, seismic data, outcrop and core study, etc. (Khoshbakht et al., 2009). Recently, image logging is evolving into the most effective way because it is intuitive, and has a high recovery factor in fractured zones (Rajabi et al., 2010). Image logging is the technology based on the log response to a certain physical quantity, such as wave velocity and resistivity. It is believed that the development of image logging techniques has greatly improved the detection precision of natural fractures.



(a) (b)

Fig 1. (a) Geographic location of the research area; (b) geothermal gradient map of northern Songliao Basin (Zhang et al., 2014).