Energy 129 (2017) 101–113

Contents lists available at ScienceDirect

Energy

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

Sensitivity analysis of deep geothermal reservoir: Effect of reservoir parameters on production temperature

Musa D. Aliyu, Hua-Peng Chen*

Department of Engineering Science, University of Greenwich, Chatham Maritime, Kent ME4 4TB, UK

ARTICLE INFO

Article history:
Received 19 December 2016
Received in revised form
10 March 2017
Accepted 15 April 2017
Available online 21 April 2017

Keywords:
Deep geothermal reservoir
Human-controlled parameters
Naturally-occurring parameters
Finite element modelling
Factorial experimental design

ABSTRACT

This study aims to guide reservoir engineers/managers in the selection of a combination of parameters from amongst various possible alternatives in developing deep geothermal reservoirs which can meet the desired temperature at the production wellhead for sustainable energy production. The work presents an approach for predicting the long-term performance of a deep geothermal reservoir using multiple combinations of various reservoir parameters. The finite element method and factorial experimental design are applied to forecast which of the parameters has the most influence on long-term reservoir productivity. The solver employed is validated using known analytical solution and experimental measurements with good agreement. After the validation, an investigation is then performed based on the Soultz lower geothermal reservoir. The results showed that fluid injection temperature is the parameter that influences the experiment the most during exploitation involving production temperature, whereas injection pressure rate happens to have a more significant impact on reservoir cooling.

1. Introduction

Geothermal energy production is, and for the predictable future will remain, one of the most important activities that can provide a solution to the current clean and sustainable energy demand in the world. The objective is to discover and produce energy located at a great depth in an efficient way by applying a synergy of various scientific disciplines (geology, geophysics, seismology, and reservoir engineering). In a deep geothermal system, reservoir rock parameters determine the value of accumulated heat and energy [1]. Their quantity and productivity also ascertain the value of the accumulated energy. In reservoir management, both production rate and producibility are functions of the rock and reservoir fluid parameters [2]. For example, the capacity of a well depends on rock parameters (permeability, porosity, reservoir thickness), on fluid properties (density, viscosity), on the well type (vertical, horizontal), and on the pressure drop applied at the bottom hole. Also, the productivity of a geothermal well depends, among other things, upon the permeability of reservoir formation to those fluids, and anything that increases the permeability of the formation will increase the rate of energy production. Injection fluid in geothermal energy exploitation is one of the most important parameters that can be controlled during operations. This is because the fluid is heated to a precise temperature before injection. Mostly, after extracting the fluid back for usage, it is then transferred to a cooling tower for reinjection/reuse. The wellhead pressure and its relation to the flow rate of fluid via the turbine is an additional parameter that must be considered when generating power from geothermal resources. Likewise, the well spacing is decided by an ease of drilling and also by the evidence that the geothermal resource enclosed by the well pattern must be extracted during an economically acceptable period of 30 years [3]. This factor is determined by the fluid properties, the well capacity, the reservoir parameters, and distribution. If the exploitation of a geothermal reservoir takes place by so-called enhanced geothermal system (EGS) methods (as in this study), the well spacing is significantly less than in the case of production via the primary method [4].

Therefore, the interaction of this parameter with others can provide deeper insight into reservoir management. For instance, permeability is one of the fundamental parameters of a reservoir that controls the fluid flow in a deep geological formation. Reservoir stimulation increases the permeability of a system due to stress perturbation taking place as exploitation proceeds. However, coupled hydro-thermal analyses is not a candidate to capture the effect of such changes in permeability when simulating, though varying the values can provide a close solution to the real life

* Corresponding author.
E-mail address: H.Chen@greenwich.ac.uk (H.-P. Chen).

http://dx.doi.org/10.1016/j.energy.2017.04.091
0360-5442/

scenario. On the other hand, porosity is another parameter that contributes in enhancing reservoir productivity because it concerns the volume fraction of the rock matrix to the pore space [5]. It is tough to estimate the porosity values for an entire matrix block in deep reservoirs due specifically to the limitations of the current measuring techniques [6]. Thus, it is expected to range the porosity values and examine their effect on reservoir productivity. Thermal conductivity, on the other hand, signifies the ability of material to transfer heat [7]. In deep subsurface systems, the value of the thermal conductivity of a formation is dependent on temperature, pressure, and porosity [8].

It is observed from the literature [9–14] that, as far as the application of finite element heat transfer and fluid flow problems to geothermal energy are concerned, a lot of studies are available. However, no study appears to be available that deals with multiple parameter interactions in geothermal energy exploitation. Based on this, the objective of the present study is to explore the possible combination of critical parameters in a deep geothermal reservoir that can meet a certain production temperature requirement during a long-term simulation of 60 years. The work identifies two group of parameters, which are human-controlled and naturally-occurring parameters, and their interactions provide preliminary indications of the potential productivity of a geothermal reservoir. A three-dimensional (3-D) model of the Soultz (France) deep geothermal reservoir is developed on COMSOL FE package, which is a commercial software that allows the implementation of user-defined subroutines from the MATLAB programming language in the simulation. The package is widely employed in industries and institutions for its capability to accommodate extensive material modelling and the coupling of several systems in finite element analyses. Before running the analysis, the numerical code is validated first with known analytical solution and experimental measurements to ascertain the capability of the chosen simulator. In the reservoir analysis, the required temperature fields are calculated by solving a forward problem using the finite element method. For predicting the possible combinations, a complete factorial experimental design is chosen for the analyses.

In this study, the sensitivity analysis is limited to the maximum and minimum values of the reservoir parameters analysed. Knowing the influence of a certain parameter under a minimum or maximum value when combined with other parameters will provide an understanding of which of the values is significant. Besides, it reduces the computational cost without compromising the outcome of the analysis. For example, lateral well spacing, as a human-controlled parameter when narrowly spaced, will likely result in short-circuiting, whereas wider spacing makes it harder to establish a connection between the wells. Therefore, careful considerations have to made when selecting the minimum or maximum value of the reservoir parameters. The various parameters are taken from the general engineering observation's point of view in the real field case for the Soultz geothermal reservoir.

2. Mathematical background

The finite-element method is used for solving the macroscopic transient coupled equations of heat transfer and fluid flow in a fully saturated and fractured porous medium as implemented in the forward modelling code chosen. Thus, the dual porosity-permeability approach is employed in solving the macroscopic partial differential equations (PDE's) for both the matrix and fracture systems. In this approach, the rock matrix is considered to have high porosity and low permeability, while the fracture, on the contrary, has low porosity and high permeability. The irregular fracture system crossing the matrix provides perhaps the recovery of the accumulated heat and energy.

2.1. Governing equations

The macroscopic equations describing heat and fluid transport in fractured and saturated porous media can be numerically investigated by coupling the appropriate rock and fluid physical properties, respectively. For the heat transport, the transfer in porous matrix is governed by both conduction and convection [15], which is written as

$$\rho C_P \frac{\partial T}{\partial t} + \rho_L C_{P,L} v \cdot \nabla T - \nabla(\lambda \cdot \nabla T) = 0 \tag{1}$$

where ρ and C_P are the effective densities and specific heat capacities, respectively, T is the temperature, and t is time. Properties, ρ_L and $C_{P,L}$ corresponds to fluid density and specific heat capacity, v is Darcy's velocity and λ is the effective thermal conductivities. The properties of the porous media obey a simple mixing rule between solid (S) and liquid (L), expressed as

$$\rho C_P \ = \ \phi(\rho_L C_{P,L}) \ + \ (1-\phi)\rho_S C_{P,S} \tag{2}$$

$$\lambda \ = \ \phi(\lambda_L) \ + \ (1-\phi)\lambda_S \tag{3}$$

here ϕ is the porosity and ρ_s is the solid density. Properties, λ_L and λ_S are the fluid and solid thermal conductivities, respectively.

For the fluid flow within a matrix block [16], the equation writes

$$\rho_L S \frac{\partial P}{\partial t} \ + \ \nabla \cdot \rho_L v \ = \ 0 \tag{4}$$

where S is the linearised storage, and P is the fluid pressure, and Darcy's velocity v is written as

$$v \ = \ -\frac{\kappa}{\mu}(\nabla P \ - \ \rho_L g \nabla z) \tag{5}$$

here κ is the permeability, μ is the fluid viscosity, g is the acceleration due to gravity and z is the depth.

Similarly, the heat transport in fractures within a porous matrix is given by

$$\rho C_P \frac{\partial T}{\partial t} \ + \ \rho_L C_{P,L} v_f \cdot \nabla T \ - \ \nabla(\lambda \cdot \nabla T) \ + \ Q_{f,E} \ + \ Q_{m,E} = \ 0 \tag{6}$$

parameters, $Q_{f,E}$ and $Q_{m,E}$ corresponds to the energy sources/sinks for the fracture and matrix block. The fracture Darcy's velocity term v_f is expressed as

$$v_f \ = \ -\frac{b^2}{12\mu}\left(\nabla P_f \ - \ \rho_L g \nabla z\right) \tag{7}$$

where b is the fracture aperture, and P_f is the fluid pressure within the fracture. The fluid flow within the fracture is written as

$$\rho_L S_f \frac{\partial P_f}{\partial t} \ + \ \nabla \cdot \rho_L v_f \ + \ Q_f \ + \ Q_m = \ 0 \tag{8}$$

where Q_f and Q_m are the fluid mass sources/sinks for the fracture and matrix block and S_f is the fracture storativity.

Coupling between the fluid motion and heat transport is carried out through ρ_L, μ, $C_{P,L}$, and λ_L parameters that appear in almost all Equations (1)–(8), which are coupled by the temperature field (T), since all the properties are temperature-dependent, which will be discussed later. Also, the coupling between heat transport and fluid flow is achieved through Darcy's velocity term (contribution of convective heat transfer) that appears in Equations (1), (4) and (5) for the matrix block, and (6), (7) and (8) for the fracture.