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Performance evaluation of enhanced geothermal system (EGS): Surrogate models, sensitivity study and ranking key parameters

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ABSTRACT

Designing an efficient system to extract heat from an enhanced geothermal system (EGS) requires proper understanding of the behavior of the reservoir over a long period. Five key parameters namely well spacing, fracture spacing, well inclination angle, injection temperature and injection rate are considered in this study for a doublet well system. To study and evaluate the performance of an EGS, second order surrogate models for 'produced water temperature', at certain time intervals are developed as a function of these five factors. The in-situ properties of a candidate reservoir for designing the simulations are taken from the FORGE site, Utah. Simulations are designed using 'Box-Behnken' design of experiments techniques to minimize the number of simulations. The models are trained and tested with the simulated results. Fitness of the models is calculated by estimating the errors using the coefficient of determination (R^2) and the normalized root mean square error (NRMSE). These surrogate models are used to study the sensitivity of the aforementioned factors on the temperature of the produced water and the heat recovery over a time period of 30 years. Finally, the hierarchy of factors, as they impact the total heat recovery are represented as a tornado plot.

1. Introduction

Although geothermal energy has been studied since the early 1900s, recently it emerges as a potential renewable source of energy [1–3]. Geothermal reservoirs also known as hot dry rock [4,5], usually should have three key properties, high temperature (200+ °C), highly conductive natural fracture system and availability of a working fluid to bring that heat to the surface. Usually it is possible to find high temperature reservoirs (at economically accessible depths) but the possibility of finding a highly conductive fracture system in such reservoirs is less likely. The development of enhanced geothermal system (EGS) has been visualized as a breakthrough because it only relies on the availability of high temperature reservoirs. It conceptually consists of drilling two or more parallel or near parallel wells (a few hundred meters apart, for example). These are connected by developing a network of hydraulic fractures in the reservoir, hence eliminating the requirement of a naturally occurring fracture system. One or multiple wells can be used to inject the working fluid (usually water) into the reservoir (via hydraulic fractures exiting the injection wells), allowing the fluid to extract the heat. This heated fluid is produced from the remaining wells (production wells). The network of fractures plays an important role because it increases the surface area inside the reservoir that is used to enhance the heat transfer rate from the reservoir to the working fluid.

Creating an efficient EGS is a major challenge faced by the industry. It requires a huge capital investment [4] and hence calls for the proper planning, design and development of the system. It is important to have a better understanding of the key parameters and their effect on the performance of the EGS. A good EGS system is able to generate sufficient heat to produce electricity and is sustainable for at least 30 years. One way to ensure proper planning of an EGS is by carrying out simulations to emulate the reservoir and then trying out various combinations of the five key parameters to enhance the performance. Unfortunately, this method takes quite a long time since all of the possible combinations need to be evaluated before choosing the best one. To get around this problem it is feasible to study the impact of individual parameters and rank them and then use this to optimize the design program. This helps to develop an efficient system in less time.

There have been studies focusing on different type of EGS to evaluate their performance. Sanyal et al. [5] studied a five-spot layout of a 3D EGS model (hypothetical) with one injection and four production wells. They analyzed their optimal performance on the basis of fracture spacing, reservoir permeability, and well

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geometry. Frash et al. [6] carried out studies on drilling doublet and triplet well systems (a triplet with one injector and two producer wells). They mentioned the importance of proper well trajectories to ensure that the wells intercept the hydraulic fractures to allow the fluid to be circulated. Sun et al. [7] evaluated the effect of different fracture geometries on heat extraction from the reservoir. Cao et al. [8] studied the effect of carrier fluid on the heat extraction. Guo et al. [9] investigated the effects of aperture heterogeneity on flow pattern evolution for only for a single fracture in an EGS. Chen et al. [10] showed that the performance of EGS would not increase by simply drilling more production wells. Later on, Chen at al [11]. performed sensitivity analysis on doublet EGS, and concluded that the heat extraction rate and life of the system is dominantly depended on the flow pattern in the reservoir. Zeng et al. [12] studied the performance of 2D EGS model with a horizontal doublet well layout. They concluded that the energy efficiency is the function of the reservoir permeability and the flow rate of water in the system. Jiang et al. [13] designed and simulated a 3D conceptual EGS with a triplet well layout operating over 40 years and concluded that it performs much better that the doublet system and elongates the lifespan of the system by 10 years. Other studies that have been carried out also include the simultaneous effects of two or more parameters. Xia at al [14]. performed a sensitivity study on fracture spacing, deviation angle of the parallel wells, and injection flow rates. Aliyu et al. [15] considered the effects of injection flow rate, fluid injection temperature, and lateral well spacing. Ekneligoda et al. [16] studied the effect of mass flow rate, number of fractures, fracture width, and production time on the EGS to obtain the fracture length and the half spacing for the system. Although these studies help to understand the importance of choosing the right values for the given parameters, they don't explore the impact of a particular parameter and the combined effect on the performance of the EGS.

The objective of this study is not only to determine the key factors that affect the efficiency of the EGS, but also to determine the effect of each individual parameter. The effect of each parameter on the total heat extraction is also studied. A step-wise approach to developing a high performance EGS is also discussed. On basis of the implementation stage in the EGS, the factors are grouped into three categories, natural parameters, completion parameters and operational parameters. The key factors that are analyzed and investigated in this study include well spacing, fracture spacing, well inclination, fluid injection temperature and fluid flow rate. All of these factors were studied individually to determine their impact on the heat recovery efficiency of a typical EGS over its lifetime.

2. Method of energy extraction

The earth's crust is a vast reservoir of heat source. The temperature increases with the depth depending on the geothermal gradient which varies with locations. Drilling to excessive depths becomes increasingly expensive. It is preferable to choose sites which have high temperature reservoirs at relatively shallow depths. The temperature and the dimension of the reservoir play an important role in deciding the heat capacity and life of the geothermal system. Two or more wells can be drilled into the reservoir, accessing this huge heat source, which are subsequently connected by a network of hydraulic fractures. A fluid is circulated in the system (which acts as a heat carrier), to extract the heat from the sub-surface to the surface. When this working fluid passes through the network of hydraulic fracture it comes in contact with the hot rock, where it extracts heat via convection and conduction. The driving factor for heat transfer is the temperature gradient between the reservoir and the fluid. The rate of heat transfer also increases with the temperature difference between the rock and fluid increases. This implies that a cooler fluid extracts more heat than a warmer fluid in the same amount of time. In addition, the surface area of the fracture network plays an important role because it facilitates the interaction of the fluid with the hot reservoir rock. If the fracture network is widespread and has good conductivity, there is an increased rate of heat transfer. Once the fluid comes back to the surface, a heat exchanger is used to extract the heat from the fluid before reinjecting it into the system.

3. Enhanced geothermal system (EGS)

EGS is a method of creating a fluid circulation system to extract the heat from the reservoir. An EGS is visualized to consist of an injection well, a production well and multiple stages of hydraulic fractures as shown in a schematic diagram in Fig. 1.

The fracture network provides an interaction pathway for the fluid and the reservoir rock. It also connects the injection and production wells to complete the circuit. Many possible combinations can be used in an EGS to extract the heat from the reservoir. In this study, a simple doublet system is used, consisting of an injection well and a production well, connected by multiple vertical hydraulic fractures. The working fluid used here is water because it is generally available and has a high heat capacity. The entire system is operated in a closed loop with a make-up line to account for fluid losses in the reservoir. The water is pumped under high enough pressure to maintain its state as liquid, which proves beneficial as this eliminates any fluid losses that may occur during flashing of the liquid (to extract heat) and also saves time as the water is not required to be condensed before reinjecting. The potential of any geothermal project can be determined by evaluating three parametric groups (categorized on the basis of their implementation stage), namely natural properties, completion parameters and operational parameters.

Natural properties are intrinsic properties of the geothermal reservoir and is the first stage for development of EGS. These include the thermal gradient of the system, the heat capacity, thermal conductivity, density of the formation, size of the reservoir and availability of natural fracture networks. These in-situ

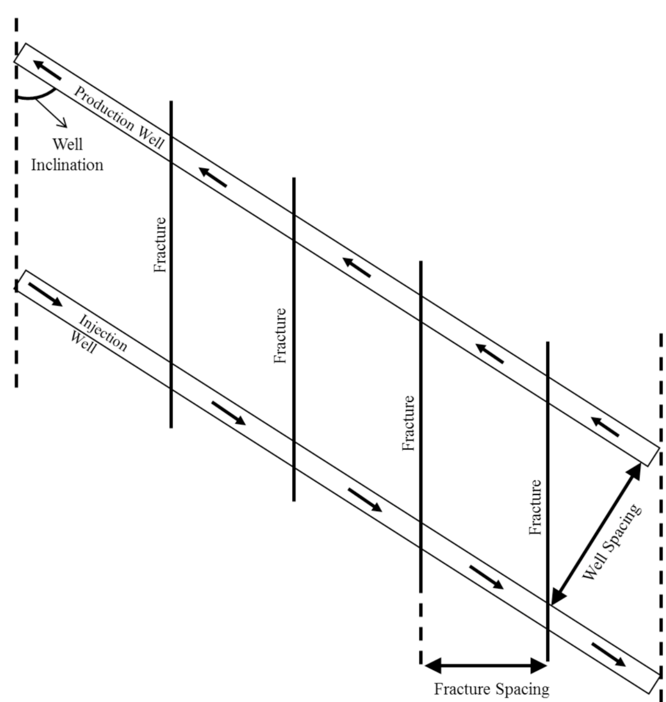

Fig. 1. Schematic diagram of a doublet EGS with multiple fractures (elevation view).