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Development of hot dry rocks by hydraulic stimulation: Natural fracture network simulation

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Abstract

This paper presents an advanced computational modelling of natural fracture networks in HDR (hot dry rock) reservoirs. The model stochastically simulates discrete properties of natural fractures, utilizing multi-set orientation and fractal mathematics. The simulated fracture networks are essential for further stimulation and fluid flow studies. The model has been verified using the data of actual fracture stimulation programs conducted by Gas Research Institute and Department of Energy at the multi-site. It is validated that the simulated fracture distribution is sufficiently similar to that observed in the reservoir. This paper also examines the detrimental effects of the simulated natural fracture network on the stimulated fluid flow capacity. The effective permeability enhancement (due to hydraulic stimulation) is found almost proportional to the density of the reservoir natural fractures.

Keywords: Natural fractures; Hot dry rock; Stimulation; Stochastic simulation; Permeability enhancement

1. Introduction

HDR resource, exploited as heat from rocks at temperatures above 150 °C and a few kilometres below the earth's surface, are one of the few environmental-friendly energy resources with vast potential. Unlike the conventional coal and petroleum resources that account largely for the high level of carbon dioxide emission and other environmental issues, HDR energy is virtually pollution-free (Fig. 1) [1]. The annual HDR energy production in the world is about 255 trillion watt hours (TWh), which is equivalent to a saving of 430 million barrels of fossil-based oil. Increased exploration and production of HDR resource are largely a response to oil price rises, possible fossil fuel shortages and growing concerns about carbon emissions. The importance of HDR resource is being felt in recent years and likely to grow as the needs for sustainable energy sources intensify.

The common approach to extracting energy/heat from HDR reservoirs generally requires drilling two or more wells into a high-temperature formation. Cold water is injected down one well, forced through the system of rock matrix and fractures, where it picks up heat. Hot water flows up the production wells to the surface power plant. Upon cooling, the water is pumped back down the injection wells in a closed re-circulation system,

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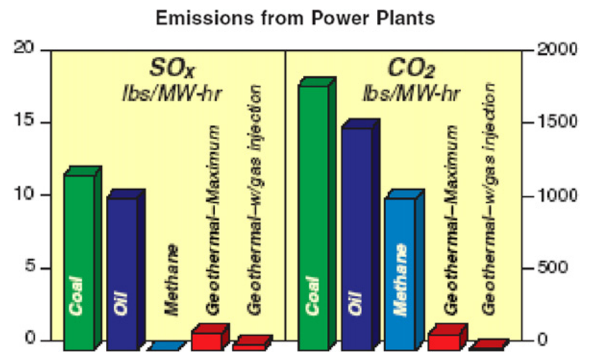

Fig. 1. Comparison of emissions from major energy sources: exceptionally low emissions from HDR sources [1].

minimising the environmental impact while increasing efficiency (Fig. 2). Most of the time, the circulation of water from injection to production wells is only possible when a network of flow paths is artificially created (e.g. by hydraulic stimulation). This activity converts a HDR region to an ''engineered HDR reservoir''. Development of a HDR reservoir can be divided into two major steps, in regards to the following critical questions [2]:

1. What are mechanical properties of the rock matrix and fracture system?
2. How do the forced-circulating water and accompanying steam flow through the rock matrix and fracture system?

This paper presents an advanced simulation of the natural fracture networks in HDR (i.e. before any stimulation), whose scope is on answering the

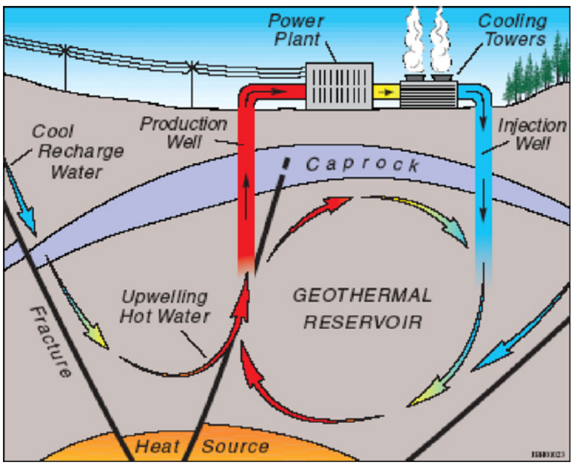

Fig. 2. Schematic development of a HDR injection–production [1].

first question. This paper also examines effects of the simulated natural fracture network on the stimulated fluid flow capacity (i.e. after stimulation). The results will be validated using the data of actual fracture stimulation programs conducted by Gas Research Institute and Department of Energy at the multi-site.

2. Simulation of naturally fracture networks

Simulation of naturally fracture networks is a complex procedure of generating numerous fractures in a block of rock processing geologic, geophysical and engineering data so that the generated fractures are conditioned/ constrained to represent real fractures in the reservoir. Fracture characteristics, which are conditioned, include fracture location, size, orientation, density, etc. The simulated fracture networks have to be discrete (object-based) and accurate, which would allow an effective and accurate evaluation of hydraulic stimulation designs [3] (see Table 1).

Earlier mathematical models for fracture networks and flow through them include equivalent continuum models [4] and discrete network models [5]. In general, the methods employ simple mathematical formulations and geomechanical processes to present complexity of fracture systems. Despite the obvious benefits of being straightforward applications, the methods are not sufficient and erroneous in simulating ''real'' natural fracture networks [6].

There are also hybrid techniques that combine deterministic and stochastic simulation for better results [7–9]. Based on the fractal concept, equivalent

Table 1
Input data used for the simulation

Rock properties	C sand	B sand
Young's modulus (GPa)	37	32
Poisson's	0.18	0.20
Density (kg/m^3)	2700	
Basic friction angle (degree)	40	
In situ permeability, K_0 (m^2)	6×10^{-17}	
Fracture sets	Dip	Azimuth
7B and 7C sands (degree)	80–82	220–230
Fracture density (m^2/m^3)	0.5	
Fractal dimension	2.1	
Maximum stress azimuth, α_H (degree)	286 (N74°W)	

Stresses	σ_v (MPa)	σ_H (MPa)	σ_h (MPa)
C sand	32	29	21
B sand	37	29	21