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Thermal breakthrough calculations to optimize design of a multiple-stage Enhanced Geothermal System

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A B S T R A C T

We perform an optimization and sensitivity analysis for design of an Enhanced Geothermal System (EGS) with horizontal wells and multiple fracturing stages. The sensitivity analysis includes calculations of thermal breakthrough and the maximum flow rate that can be achieved through the system. The analysis uses idealized reservoir geometry and is intended to investigate the relationship between parameters and provide insight into how to optimize an EGS, not to provide precise predictions of performance. Conventionally, EGS wells have been nearly vertical and stimulated with openhole completion in a single stage. This study investigates a design with two parallel horizontal wells. The first well is drilled and completed with casing, and then stimulated sequentially in stages with cased hole packers rated to high temperature. The second well is drilled through the stimulated region created around the first well and completed openhole. For different combinations of well spacing, lateral length, formation permeability, and number of stages, we calculate the optimal flow rate that maximizes the present value of revenue. The calculations show that stimulating with multiple stages greatly improves economic performance, delays thermal breakthrough, and allows a higher flow rate to be circulated through the system. At low well spacing and low number of stages, it is optimal to circulate fluid more slowly than the maximum possible rate in order to delay thermal breakthrough. With greater well spacing and with more stages, thermal breakthrough is relatively delayed, and it is optimal to circulate at the maximum possible flow rate. Overall, it is optimal to use the lowest well spacing where present value is maximized by circulating at the maximum possible rate. When it is optimal to circulate at the maximum possible rate, present value is sensitive to reservoir transmissivity. When it is optimal to circulate at less than the maximum possible rate, present value is unaffected by reservoir transmissivity. Increasing lateral length beyond 1000 m is only beneficial for designs with relatively low lateral spacing and a large number of stages.

1. Introduction

1.1. Premise

We perform a sensitivity analysis to investigate how various parameters affect the economic performance of an Enhanced Geothermal System (EGS) with horizontal wells and multiple fracturing stages. The calculations use a simplified representation of the reservoir. The objective is to investigate relationships between variables and build insight into optimal EGS design, rather than to provide precise predictions of reservoir and economic performance. The overall results are not dependent on the details of the specific parameters chosen.

A full economic analysis would require consideration of cost, the sale price of electricity, discount rate, reservoir temperature, depth, and other factors. These subjects are outside the scope of this paper. Project revenue in particular cases could be significantly higher or lower, depending on conditions.

Most EGS projects have been performed with a single fracturing stage in nearly vertical wells with openhole completion. A few exceptions are the Schönebeck project, which used packers in several stimulation stages (Zimmermann et al., 2010), AltaRock's Newberry project, which used diverting agents (Petty et al., 2013), and Petratherm's Paralana project, which stimulated from perforated casing in a vertical well (Bendall et al., 2014).

In this study, the performance of an EGS doublet involving flow between parallel horizontal wells is investigated. Multiple stage stimulation is achieved with zonal isolation technology (such as

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List of variables

A	Cross-sectional area of the wellbore
BHP_{prod}	Bottomhole pressure of the producer, MPa
BHP_{inj}	Bottomhole pressure of the injector, MPa
c_W	Heat capacity of water, kJ/(kg °C)
c_R	Heat capacity of rock, kJ/(kg °C)
(dp/dz)	Total pressure gradient, Pa/m
$(dp/dz)_F$	Frictional gradient, Pa/m
$(dp/dz)_H$	Hydrostatic gradient, Pa/m
$(dp/dz)_A$	Accelerational gradient, Pa/m
d	Well or pipe diameter, m
E	Electricity production, kW-hr
eff	Efficiency of conversion of thermal energy to electrical, unitless
f	Moody friction factor
H	An arbitrary length used in the Gringarten et al. (1975) solution, m
h	Fracture height, m
i	Discount rate
K_R	Thermal conductivity of rock, J/(m s °C)
L	Spacing between injection and production well, m
N	Number of stages
n	Total years of production
P	Price of electricity, cents/kW-hr
PV	Present value of revenue, $
Q	Volumetric fluid flow rate per fracture per unit height, m^2/s
Q_{prod}	Rate of thermal energy production, J/s
Q_{th}	Rate pf thermal energy production, kW
q	Fluid flow rate, kg/s
Re	Reynolds number, dimensionless
s	Laplace variable, dimensionless
T	Fracture transmissivity (product of permeability and thickness), m^3
T_{RO}	Initial reservoir temperature, °C
T_{WO}	Injection fluid temperature entering the reservoir, °C
$\bar{T}_{WD(z_D,s)}$	Laplace transform of dimensionless fluid outlet temperature
$t_D{}^*$	Dimensionless time variable for laplace transform
t_T	Total years of production, yrs
t	Time, s
t'	Injection time considering the time lag between injection point and arrival at z, s
v	Fluid velocity, m/s
WHP_{inj}	Wellhead pressure of the injector, MPa
WHP_{prod}	Wellhead pressure of the producer, MPa
X_E	Fracture half-spacing, m
X_{ED}	Dimensionless fracture half-spacing
z	Distance, m
z_D	Dimensionless distance
z/v	Time lag between the departure of water from the injection point and the arrival at point z, s
α, β^*	Dimensionless parameters used in the Gringarten et al. (1975) solution
ΔP_{inj}	Pressure drop in the injector, MPa
ΔP_{prod}	Pressure drop in the producer, MPa
ΔP_{res}	Pressure drop in the reservoir, MPa
ΔT	Temperature difference in the surface power plant, °C

List of variables

Δt_j	Duration of time period j, hours
ε	Pipe roughness
θ	Wellbore angle from horizontal, degrees
Λ	A dimensionless parameter used for calculating wellbore friction
μ	Viscosity of fluid, cp or MPa-s
ρ_W	Water density, kg/m^3
ω	Geothermal gradient, °C/m

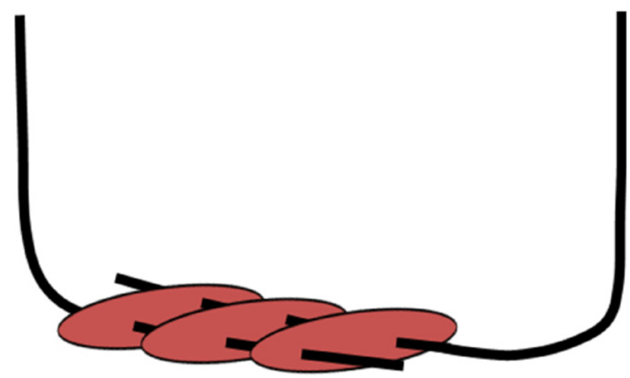

Fig. 1. An EGS doublet of horizontal wells connected by vertical fracture stages (normal or strike-slip faulting regime). The wells are oriented toe to heel in order to encourage equal flow rates between stages. The ellipses represent regions of fracturing, are not intended to be representations of the actual fracturing geometry.

packers). The laterals are oriented so that the stimulated region at each stage forms transverse to the lateral, as shown in Fig. 1. Related designs have been discussed by Gringarten et al. (1975), Cremer et al. (1980), Green and Parker (1992), MacDonald et al. (1992), Jung (2013), Glauser et al. (2013), Shiozawa and McClure (2014), Lowry et al. (2014), Olson et al. (2015), and Doe and McLaren (2016).

Orienting the laterals in opposite directions would help promote uniform flow between the stages (discussed in more detail by Shiozawa and McClure (2014). The wells could be drilled from the same pad (the same surface location), sharing surface facilities such as the mud pit, and with their wellheads located in close proximity. They could be deviated in opposite directions with only modest increase in drilling cost. For example, wells drilled vertically to a depth of 500 m and then deviated at 11.2° from vertical in opposite directions would achieve separation of 1 km at a depth of 3 km, with increase in well length of only 50 m for each well. Additional wells could be drilled from the same pad by using directional drilling to separate the wells laterally. Drilling a large number of wells from the same pad reduces surface footprint and cost (Ogoke et al., 2014).

If drilling horizontally is considered too technically challenging due to high temperature and hard rock, a similar design could be achieved by connecting two wells deviated from vertical. However, in this case, it would not be possible to orient the wells in opposite directions and different stages would be at different temperatures, which would make it more difficult to achieve uniform flow between stages.

Our prior work investigated how using multiple stages increases the maximum achievable flow rate through the system (Shiozawa and McClure, 2014) and delays thermal breakthrough (Li et al., 2014). This paper extends our prior work by using a finite fracture-spacing analytical solution and an improved optimization scheme.