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A prototype design model for deep low-enthalpy hydrothermal systems

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ABSTRACT

This paper introduces a prototype design model for deep low-enthalpy hydrothermal systems. The model predicts, empirically, the lifetime of a hydrothermal system as a function of reservoir porosity, discharge rate, well spacing, average initial temperature of the reservoir, and injection temperature. The finite element method is utilized for this purpose. An extensive parametric analysis on a wide range of physical parameters and operational scenarios, for a typical geometry, has been conducted to derive the model. The proposed model can provide geothermal engineers and decision makers with a preliminary conjecture about the lifetime of a deep low-enthalpy hydrothermal system. The proposed modelling technique can be utilized as a base to derive elaborate models that include more parameters and operational scenarios.

1. Introduction

Hydrothermal systems (also known as doublets) are the most common method of geothermal energy recovery that utilize two wells, one for hot water production and another for cold water injection. Accurate prediction of both the lifetime and energy production of geothermal doublets is essential for the successful design of such systems [1].

A significant number of studies have identified various factors influencing heat flow in geothermal reservoirs and their lifetime, including: viscosity and density dependence on temperature [2–4]; porosity and permeability [5–7]; geothermal fluid salinity [8]; flow rate [9]; well spacing [10]; injection temperature [11], and reservoir geometry [12]. These studies qualitatively identified the significance of the examined factors on the lifetime of geothermal systems, but as yet no quantitative models have been introduced that combine these factors in a simple mathematical formulation. This paper focuses on this issue.

The objective of this work is the development of a prototype model capable of estimating the lifetime of hydrothermal systems. The model is suitable for conducting a preliminary design that can be utilized by geothermal engineers and decision makers at an early stage of a project. The model estimates the lifetime as a function of typical physical and human controlled parameters, including reservoir porosity, reservoir initial temperature, discharge rate, well spacing, and injection temperature. Reaching this objective requires conducting an extensive parametric analysis examining the behaviour of the system for different reservoir parameters subjected to different operational scenarios. As the model is taking this combination of physical and human controlled parameters into consideration, the geometry should comprise all significant components, including the wellbores, the reservoir and the surrounding formation.

Modelling deep geothermal systems involves solving the nonlinear conductive-convective heat flow occurring in a complicated and disproportionate geometry. This inevitably requires the use of a numerical solution tool, for which the finite element method is one of the most suitable. Deep geothermal systems consist of very slender wellbores embedded in a vast soil mass. This geometrical peculiarity exerts an enormous computational burden, as a combination of very small elements and much larger elements is normally needed to discretize the physical domain. The problem gets even more complicated in the presence of nonlinear heat convection and fluid advection. For a three-dimensional system at a regional level, this normally requires hundreds of thousands to millions of elements, making the CPU time unrealistic for engineering practice. Currently, several models have been developed to simulate heat and fluid flow in geothermal reservoirs and wellbores. Different computational tools based on the finite difference,

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finite volume and finite element methods are available. They can be divided into two categories: reservoir simulators, and wellbore simulators. Saeid et al. [8] provide an overview of the available models and simulators.

To tackle the mesh size problem, a hybrid meshing technique is adopted here. This technique entails reducing the spatial discretization of the wellbore from 3D to 1D, and the surrounding formation from 3D to 2D, whereas the reservoir is kept as 3D. A pseudo 3D model presented by Saeid et al. [8] is used to simulate the wellbores, using 1D elements. The soil formation surrounding the wellbores and the reservoir are modelled using standard 2D and 3D finite elements, respectively. This kind of dimensional reduction saves a significant number of finite elements, making the numerical analysis feasible.

The finite element package COMSOL is utilized as a framework for implementing the proposed model and making the necessary coupling between the wellbores, soil formation and reservoir. The thermal interaction between these sub-domains is calculated simultaneously. Heat flow in the surrounding formation is modelled as linear conductive and, in the reservoir, it is modelled as nonlinear conductive-convective due to fluid density and viscosity dependency on temperature. It is worth noting that this modelling technique can be implemented in any numerical tool capable of computing heat and fluid flow in porous media and wellbores.

2. Governing equations

The physical domain of the geothermal system is decomposed into three sub-domains: 3D, 2D, and 1D, representing the geothermal reservoir and its overburden and underburden layers, the overlying soil formation, and wellbores respectively. In this section, the governing heat equations of these sub-domains are presented, together with the initial and boundary conditions.

2.1. Soil formation and reservoir governing equations

Heat flow in a deep low-enthalpy geothermal system arises from thermal interactions between the injected fluid, the initial reservoir fluid, and the surrounding formation. In a typical low-enthalpy geothermal system, fluid flow plays a major role in carrying the heat from the injection well to the production well, Fig. 1. The temperature distribution in such a system normally varies between 20 °C and 80 °C. This relatively high range of temperatures in the reservoir inevitably affects the formation fluid density and viscosity, and hence the heat flow rate and pattern. Therefore, it is vital to consider the fluid density and viscosity as functions of temperature [4].

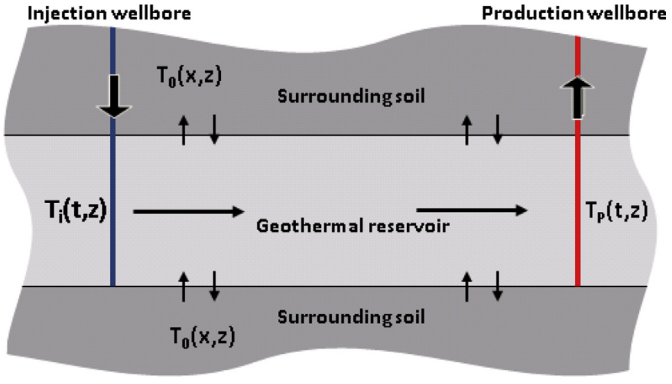

Fig. 1. A scheme of a geothermal reservoir and its interaction with wellbores and surrounding formation.

2.1.1. Heat and fluid flow in a porous domain

The macroscopic energy balance equation in a rigid (non-deforming) fully saturated medium, assuming thermal equilibrium between the solid and fluid phases, can be described as

$$\frac{\partial}{\partial t}(\rho c T) + \nabla\cdot\left(\rho_f c_f \mathbf{q} T\right) - \nabla\cdot(\boldsymbol{\lambda}\nabla T) = 0 \tag{1}$$

where T (K) is the temperature, ϕ is the porosity, ρ is the mass density (kg/m^3), c (J/kg·K) is the specific heat capacity, $\boldsymbol{\lambda}$ (W/m·K) is the thermal conductivity (considered anisotropic along the principal axis), and $\mathbf{q}$ (m/s) is the Darcy velocity. The suffix f refers to the pore fluid and s to the solid matrix. The thermal conductivity and the volumetric heat capacity are described in terms of a local volume average, as

$$\begin{aligned}\boldsymbol{\lambda} &= (1-\phi)\boldsymbol{\lambda}_s + \phi\boldsymbol{\lambda}_f \\ \rho c &= (1-\phi)\rho_s c_s + \phi\rho_f c_f\end{aligned} \tag{2}$$

The fluid flow in the reservoir can be expressed as

$$\phi\frac{\partial\rho_f}{\partial t} + \nabla\cdot\left(\rho_f\mathbf{q}\right) = 0 \tag{3}$$

where

$$\mathbf{q} = -\frac{\boldsymbol{\kappa}}{\mu}\left(\nabla P - \rho_f\mathbf{g}\nabla z\right) \tag{4}$$

in which $\boldsymbol{\kappa}$ is the intrinsic permeability (m^2) of the porous medium, μ (Pa·s) is the fluid dynamic viscosity, $\mathbf{g}$ (m/s^2) is the gravity vector, and P is the hydraulic pressure (Pa).

The brine viscosity variation with temperature and salinity can be described as [13]:

$$\begin{aligned}\mu_B =& 0.1 + 0.333S + \left(1.65 + 91.9S^3\right) \\ &\times \exp\left\{-\left[0.42\left(S^{0.8} - 0.17\right)^2 + 0.045\right]T^{0.8}\right\}\end{aligned} \tag{5}$$

and the brine density variation with temperature and salinity is described as

$$\begin{aligned}\rho_B =& \rho_w + S\{0.668 + 0.44S + 1e-6[300P - 2400PS \\ &+ T(80 + 3T - 3300S - 13P + 47PS)]\}\end{aligned} \tag{6}$$

where ρ_s and ρ_W are the saline and water densities (g/cm^3), S is the brine mass fraction (ppm/10^6), and μ_s is the viscosity (cP).

2.1.1.1. Reservoir initial and boundary conditions.

Initially, at time $t = 0$, the pressure is hydrostatic. Upon operating the geothermal system, the hydraulic boundary conditions may be described as

$$\begin{aligned}p\left(x_{\text{inj}}, y_{\text{inj}}, z_{\text{inj}}\right) &= p_1, \quad \text{at the injection well location} \\ p\left(x_{\text{pro}}, y_{\text{pro}}, z_{\text{pro}}\right) &= p_2, \quad \text{at the production well location}\end{aligned} \tag{7}$$

For heat flow, the initial condition of the soil mass, at time $t = 0$, is defined as the steady-state condition

$$T(x, y, z, 0) = T_0(x, y, z) \tag{8}$$

At the reservoir inlet, the boundary condition is