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Heat Transmission in a Geothermal Wellbore: Modelling and Application

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Abstract

A wellbore or borehole is a hole drilled in the ground to extract or explore the earth's natural resources. For extraction of geothermal heat, most geothermal reservoirs use an injection well and a production well where water is fed in and received respectively. Though effort is made to ensure efficient production, the production well is usually associated with some heat loss to the surrounding rock. An investigation of this heat loss is important for optimizing the efficiency of a geothermal reservoir. In this work, the heat equation for a wellbore surrounded by rock is formulated and solved to estimate the fluid temperature. The model takes conduction and convection into account as mechanisms for heat exchange between wellbore and surrounding rock formation. With the model, various investigations are made possible – the effect of the borehole diameter could be studied with insights into the new proposed earth energy extraction system (Triple E System). The Triple E system is a concept that uses preheating of injection fluid in a wellbore with ultra-slim diameter to overcome the limitations of conventional geothermal systems. The model could also be coupled with a geothermal reservoir model and further extended to oil reservoir wellbores especially in permafrost regions where geothermal gradient is significant.

Introduction

Estimating fluid temperature especially in a production well helps in determining the efficiency of geothermal energy extraction. Various wellbore heat transfer models originally developed for oil and gas applications also find relevance in geothermal wellbores. Generally, research in geothermal wellbore heat transfer is rising especially for investigation of new concepts like the earth energy extraction system [14], single well reservoirs [16], and use of CO_2 instead of steam as working fluid [10].

In a geothermal reservoir, there is the risk of cooling of the production fluid due to short-circuiting between the injection and production wells. Sanyal et al. [14] developed the earth energy extraction system (the EEE system) where injection fluid is preheated in a wellbore with ultra-slim diameter and low flow rate to overcome this problem as well as the problem of fluid loss in conventional geothermal systems. Furthermore, an understanding of the subsurface fracture network and flow is important for design of Enhanced Geothermal Systems (EGS). GEOFRAC is a 3D mechanical-based geometric model developed by Ivanova [7] for representing fractures in a geothermal reservoir. The model, which only generated fractures at inception, now has flow and heat transfer models coupled to it. Based on the heat transfer model, Li et al. [9] added a thermal drawdown model to estimate the service life of a reservoir. GEOFRAC's flow and heat transfer models do not take the wellbore into account in analysis. Thus, developing a wellbore heat transfer model will enhance the comprehensiveness of GEOFRAC as a decision aid in EGS. Masdar City is an emerging renewable energy hub powered mainly by solar energy. There have been efforts at geothermal energy extraction in the city. The developed model will also be applied to data from Masdar City geothermal well testing.

One of the pioneering works on the modelling of wellbore heat transfer is the classic work of Ramey [12]. He developed a model to predict fluid temperature in injection wells assuming single phase flow of liquid or gas. Assuming steady-state flow in the wellbore and heat transfer to the earth by unsteady radial conduction, he extended the model's capability to account for heat loss from the wellbore to the surrounding formation. Horne and Shinohara [6] expanded Ramey's model to estimation of fluid temperature and heat loss in injection and production wells of a geothermal reservoir. Willhite [17] provided methods of estimating the overall heat transfer coefficient in Ramey's formulation for various configurations; only conduction and convection were considered.

Ramey's model was further extended to facilitate changes in well deviation, variable thermal properties and two-phase flow while accounting for Joule-Thomson effects due to heating or cooling caused by pressure changes in the flowing fluid [2,4,13]. In most of these models, analytical solutions were obtained for fluid temperature. As pointed out by Skoczylas [15], analytical solutions have limitations especially when effects like change in boundary condition and ground properties over time are to be considered. In such cases, numerical methods are more appropriate. Ouyang and Belanger [11] used the finite difference method to numerically solve the wellbore heat transfer problem. Though numerical methods are more flexible, they could be computationally more expensive. Thus, for models coupling a wellbore model to a reservoir model, analytical or semi-analytical models are used. In a semi-analytical model, an analytical expression for temperature is used for heat transfer between wellbore and formation while heat and mass transport are solved numerically (for example, [8]).

The aim of this work is to develop an analytical wellbore heat transfer model for a geothermal reservoir. This model will be applied to Masdar City geothermal well and also used to study the novel EEE system. The wellbore model developed could also be integrated into GEOFRAC to improve its modelling capabilities.

Wellbore Heat Transfer Model

To model the transport in a geothermal system, an energy balance for the wellbore fluid is required. For any fluid element, there are two heat transfer processes involved: (1) it receives heat from the surrounding rock or formation through convection, and (2) it loses heat to the surroundings through conduction. Heat transfer in the formation is first investigated. This depends on formation temperature distribution, temperature differences and the resistances to heat transfer within wellbore elements [5].

Heat Transfer in the Formation

Governing Equation

Heat transfer between the wellbore and surrounding formation is a heat conduction problem. It is governed by the 3D heat diffusion equation in cylindrical coordinates due to the geometry of the wellbore. For simplification, it is assumed that heat is conducted evenly in all radial directions (axisymmetric) and radial conduction (in r direction) is much larger than conduction in θ and z directions. A very short section is considered thereby reducing the equation to a 1D problem [4]. The governing equation thus reduces to:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad \text{where } \alpha = \frac{k}{c\rho} \tag{1}$$

T is formation temperature, k is thermal conductivity, c is the heat capacity, ρ is density and α is thermal diffusivity of formation. For any arbitrary depth, equation (1) gives the formation temperature T at time, t, and distance, r, from the center of the wellbore.

Boundary and Initial Conditions

The governing equation, equation (1), is solved for wellbores using a finite inner boundary ($r=r_w$) and an infinite outer boundary ($r\rightarrow\infty$). To simplify the relation, it is assumed that the properties of the ground do not change with time. Ramey [12] makes a further simplification that the well is treated as a line source i.e. inner boundary is infinitesimal but the approach of Hasan and Kabir [4] is adopted here wherein Ramey's solution is improved by considering the wellbore to have a finite radius. Generally, in imposing the outer boundary condition, a constant temperature is assumed. For the inner boundary, three approaches are commonly adopted: (1) constant temperature, (2) constant heat flux, and (3) convection [15]. Skoczylas [15] gives a detailed description of the three cases but the approach in [4] which is based on constant heat flux is adopted. At the outer boundary, the formation temperature is constant with respect to radial distance. At the interface between the wellbore and formation Fourier's Law of conduction is applied to give:

$$Q = 2\pi k r \left.\frac{\partial T}{\partial r}\right|_{r=r_w} \tag{2}$$

where Q is the heat flow from the formation to the well per unit length of the well and r_w is the wellbore outer radius. For the initial condition, an initial temperature distribution of the formation, T_e, is assumed which varies linearly with depth (following Ramey [12]). This assumption does not necessarily hold and could be solved in 1D as a function of z considering radiogenic heat generation as done by Zhou [18].

Solution for Dimensionless Temperature

The governing equation, equation (1), is solved by introducing non-dimensional radius (r_D) and time (t_D), thereby modifying equation (1) and accompanying boundary and initial conditions. The ensuing equation is solved for the dimensionless temperature (T_D) using Laplace transform [4]. For heat diffusion per unit well depth, Q, Hasan and Kabir [4] developed the following relation:

$$Q \equiv -\frac{2\pi k}{T_D}\left(T_w - T_e\right) \tag{3}$$

where T_e is the initial formation temperature, T_w is the interface temperature between the wellbore and formation and T_D is the dimensionless temperature function obtained from Laplace transformation. The expression in equation (3) gives the heat diffusion from formation to wellbore and wellbore to formation that applies to all wellbores regardless of their configuration [5]. The dimensionless temperature function, T_D, is a function of only dimensionless production/injection time, t_D. Since calculation of T_D is mathematically involving and computationally expensive, and it depends only on t_D, finding a correlation between T_D and t_D will significantly save computational time especially when the model is to be coupled with a reservoir model for which the present model is envisioned. Based on statistics from large well data, various relations have been developed between t_D and T_D. For the adopted constant heat flux inner boundary condition, Skoczylas [15] suggests revised Hasan and Kabir correlation which is expressed as [5]:

$$T_D = \ln\left[e^{-0.2t_D} + (1.5 - 0.3719\, e^{-t_D})\sqrt{t_D} \right] \tag{4}$$

Wellbore Resistances

In radial heat exchange between the wellbore and the formation, some resistances have to be overcome. The resisting media which are designed together with the borehole/wellbore tubing are shown in Figure 1. The fluid with temperature T_f flows through the tubing with inner tubing radius, r_{ti} and outer tubing radius, r_{to}. There is sometimes an insulator between the outer tubing and the casing which is not considered here. When there is a blow out in a geothermal well due to higher pressure of the shut-in well head, induced methods like pumping and air compression are used to force back the heat flow from the tubing. This gives rise to a space between the tubing and casing which is called the annulus. The annulus affects the heat flow in producion wells of EGS and is occasionally confined by sealing [3]. The annulus is usually filled with a fluid – liquid or gas with vacuum allowed in special cirmcustances [18]. There is a layer of cement that separates the casing from the formation.

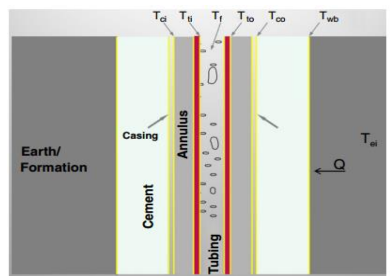

Figure 1. Section of a wellbore showing resisting media (taken from [5])

The inner tube is associated with convective heat transfer while all other layers are associated with conduction except the annulus which has radiation, natural convection, conduction or combinations of them. Though Figure 1 above was used for an oil production well, it is not different from that adopted by [18] for a geothermal well.

A single-phase flow in the tube is assumed. To obtain the convective heat transfer coefficient of the fluid, h_f, the relation for forced convection for a heat flow in an inner tubing is used.

Since metals have high conductivity and the casing and tubing have relatively thin walls, we ignore the temperature drop across the tubing and casing walls (i.e. $T_{ti} = T_{to}; T_{ci} = T_{co}$). The overall heat transfer coefficient is obtained from:

$$\frac{1}{U} = r_{to}(R_f + R_c + R_{cem}) \tag{5}$$

The heat transferred from the wellbore fluid to wellbore formation interface is given by [5]:

$$Q = -2\pi r_{to} U \left(T_f - T_w \right) \tag{6}$$

This heat flow in equation (6) should be equal to the heat transferred from the formation as given in equation (3). Equating the two and eliminating T_w , the following is obtained:

$$Q = L_R \dot{m} c_p \left(T_e - T_f \right) \quad \text{where} \quad L_R = \frac{2\pi}{c_p \dot{m}} \left(\frac{r_{to} U k}{k + r_{to} U T_D} \right) \tag{7}$$

L_R is the relaxation parameter as defined by Ramey, $\dot{m}$ is the mass flow rate of wellbore fluid, k is the earth's thermal conductivity, U is the overall heat transfer coefficient, r_{to} is the outer radius of the wellbore and T_D is the dimensionless temperature function.

Energy balance for wellbore fluid

To obtain the fluid temperature, an energy balance is performed for a control volume of the wellbore. Assuming steady state condition, single-phase water flow where pressure and velocity do not vary with depth and a linear geothermal temperature, Ramey obtained the fluid temperature for injection, $T_{f,\,inj}$:

$$T_{f,inj} = Az + B - \frac{A}{L_R} + \left(T_o(t) + \frac{A}{L_R} - B \right) e^{-zL_R} \tag{8}$$

where B is the surface temperature, T_0 is the injection temperature, L_R is the relaxation parameter and $Az + B = T_e$ is the formation temperature assuming a linear geothermal gradient. Horne and Shinohara [6] extended Ramey's solution in equation (8) to the production well to obtain:

$$T_{f,pro} = T_{ebh}(t) - Ay + \frac{A}{L_R} \left(1 - e^{-yL_R} \right) \tag{9}$$

where $T_{ebh} - Ay$ is the earth temperature and $y = L - z$ is the height above the production depth.

Simulation Results

A case of injection with mass flow rate 4790 B/D and injection temperature 58.5 °F was used to run the model for an injection time of 75 days. The casing size and tubing inner diameter are 7 in and 6.366 in respectively. The assumed geothermal temperature is 70 + 0.0083z °F/ft. The results are presented in Figure 2**.**

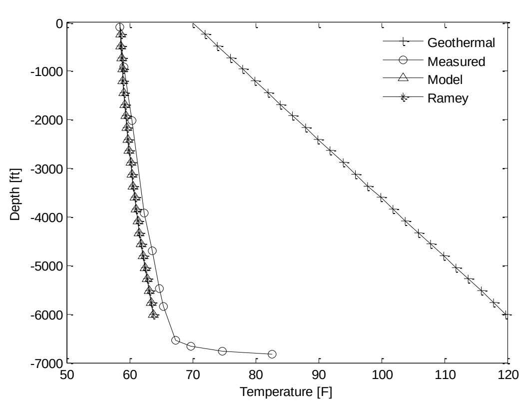

Figure 2. Comparison between simulation results and measured data for an injection well

A good match is obtained between the model which is based on Hasan and Kabir [4] and the measured temperature. The model appears to give the same results as Ramey's model which is known to work well for time exceeding one week. What makes the two models different is the dimensionless temperature function T_D.

Applications of Model

Masdar Geothermal Well

Masdar City is a growing sustainable city powered by renewable energy. Though the main power source is solar energy, two geothermal wells were built in 2010 to evaluate the prospects of geothermal energy extraction. Schlumberger Water Services dug and carried out various tests on the two geothermal wells (GW-1 and GW-2) in addition to two shallow ones (SW-1 and SW-2). The analysis showed that Masdar City has geothermal energy potential; based on the productivity and temperature characteristics, well GW-1 was proposed as production well and GW-2 as injection well. The model developed here was used to predict the well temperature profile as shown in Figure 3.

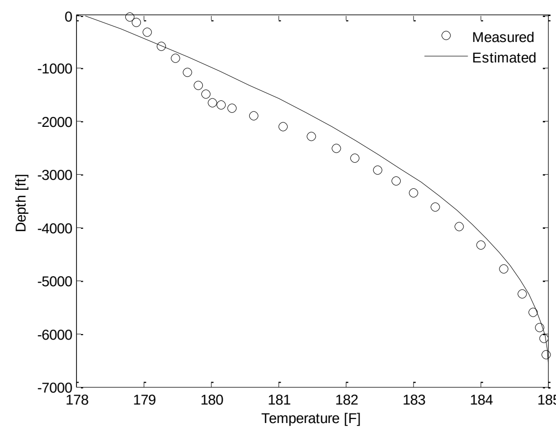

Figure 3. Temperature profile in Masdar City Geothermal Well (GW-2)

The model results compare well with the measured data as the general trend is captured. Possible differences might be attributed to geothermal gradient and wellbore casing. While the actual well had three segments of different diameters, a constant diameter was assumed in the simulation. Also, the exact geothermal gradient in Masdar City was not available, so geothermal gradient for Shuaiba formation in UAE as reported by Alsharhan [1] was used: 68 + 0.0235z °F/ft.

EEE System

The model is applied in studying the earth energy extraction system. It is observed from Figure 4 that for the conventional diameter and mass flow rate, the increase in the fluid temperature down the well is modest. However, using an ultra-slim diameter with a low mass flow rate significantly increases the temperature rise down the well. Thus, for the case of an ultra-slim diameter, the problem of cooling of production well fluid due to short-circuiting is less likely. This is because the fluid is at a higher temperature. This shows the validity of the EEE system in addressing the issue of cooling of production fluid due to short-circuiting.

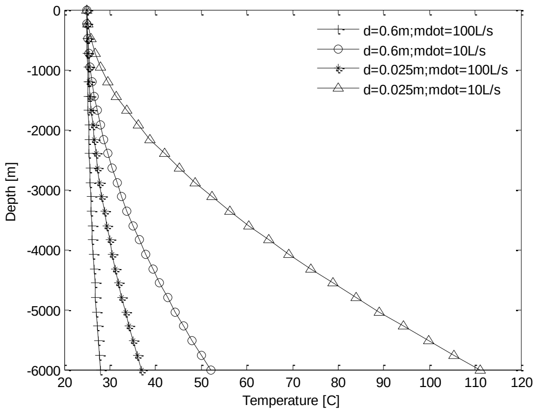

Figure 4. Comparison between conventional (0.6m) diameter and ultra-slim (0.025m) diameter for different flow rates

GEOFRAC

As hinted earlier, GEOFRAC is a mechanical based geometric model that represents fractures in a geothermal reservoir. GEOFRAC is a hybrid approach since it combines mechanical modelling with stochastic modelling to generate a discrete fracture network (DFN) model.

A flow model and a heat transfer model have been integrated into GEOFRAC using the model of flow between two parallel plates. Equation (10) represents the heat transfer model:

$$T_2 = T_r - \left(T_r - T_1\right) e^{\left(\frac{-h_f PL}{\dot{m}Cp}\right)} \qquad (10)$$

where ṁ is the mass flow rate, *Cp* is the specific heat capacity of the fluid, *L* is the fracture length, T_r is the rock/formation temperature, *P* is the perimeter of the cross-section, and, T_1 *and* T_2 are the inlet and outlet temperatures respectively. h_f is the heat transfer coefficient of the flowing fluid which depends on Nusselt number, thermal conductivity of fluid and hydraulic diameter of conduit.

Since GEOFRAC does not take into consideration the effect of the reservoir borehole, the model developed in this work could be incorporated to adjust the value of the inlet and outlet temperatures (T_1 and T_2 respectively) appropriately. This will make GEOFRAC a more comprehensive decision aid tool for Enhanced Geothermal System (EGS) design.

Conclusion

A heat transfer model for a geothermal wellbore was developed assuming a single-phase flow in the wellbore while considering transient conduction in the formation and steady-state convection for the fluid. The model was applied to Masdar City geothermal well GW-2 and a good match with measured data was obtained. It was then used to investigate the Earth Energy Extraction system which was proven to be a plausible way of preheating the injected fluid to avoid cooling of production fluid in case of short-circuiting. The model could be incorporated into GEOFRAC, a mechanical based stochastic model, to enhance its comprehensiveness in modelling fractures in a geothermal reservoir. For the future, two-phase flow could be investigated and instead of assuming a linear geothermal gradient, a more realistic analysis for initial formation temperature could be used.

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