PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Modeling Bottomhole Cooling

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Keywords: Bottomhole temperature, fluid circulation

ABSTRACT

In geothermal applications engineers have to deal with high bottomhole temperatures. In Turkey many of the geothermal power plants are located in the Buyuk Menderes Graben in Western Anatolia. Bottomhole temperatures in this region could be as high as 275 °C. High temperatures could present problems for various applications. For example, various chemicals are used to remove scaling or to prevent corrosion in a well. Some forms of chemicals will not work under high temperatures and therefore the bottom hole would need to be cooled by way of fluid injection before any chemical injection is applied. Furthermore, cement jobs for the casing can also be affected by temperatures. Hence bottomhole temperatures must be modeled accurately for appropriately treating the cement.

All of the above mentioned problems require the modeling of temperature throughout the wellbore. In this study we have developed a numerical model capable of modeling the temperatures in the wellbore. The model is based on solving the energy balance equation under steady state conditions only. The model considers the heat transfer by way of convection both in the well and the reservoir and heat transfer by way of conduction to the surrounding environment. We specifically focus on the bottom hole cooling via fluid injection and consider the effects of various well parameters on the cooling time. The parameters considered in this study are the temperature of the cooling fluid, the radius of the well-used, the injection time and/or buildup and the injection rate.

1. INTRODUCTION

Although geothermal is a preferred energy source nowadays, it contains several operational difficulties. Due to the high temperature and different reservoir characteristics compared with oil and gas reservoirs, it requires different drilling and work-over techniques then conventional ones. Therefore, the prediction of the properties especially temperature is a very critical process.

An important process to make some of the geothermal operations possible is the cooling operation either with the use of mud during drilling or use of water during other operations. As a common example, during and after some time of the acidizing operations, the temperature at the bottomhole needs to stay under the upper working temperature limits of the equipment and also the chemicals. Otherwise, the acid, chemicals and/or temperature can damage the tools and/or equipment, and temperature can decrease or destroy the effectiveness of chemicals. This would eventually lead to failure of the operation and result in loss of time and money. However, measuring of temperature during these operations could be inapplicable or unaffordable. Hence instead of running a tool to measure the temperature behavior, some mathematical approaches and/or simulations can be used. For this purpose, a mathematical model is developed to model the cooling process in the well. The model developed considers both heat transfer mechanisms of conduction and convection where necessary. The model is based on the steady state flow of fluids. It is capable of modeling the cooling during fluid flow as well as the heating after a cooling operation. One of the specific targets of this study is to estimate the time for the well temperature to reach upper working temperature limits after the cooling operation.

One of the early studies about the wellbore heat transmission problem was discussed by Ramey (1962). Ramey (1962) considered steady state conditions and focused on the estimation of the temperature of injection fluids as a function of depth and time. The model is developed for different injection fluids as hot water, cold water, air, hot natural gas etc. and derived an approximate solution for the transient heat conduction problem into the formation.

The solutions for both the wellbore and reservoir simulations have been studied by Hadgu et al. (1994). They tried to couple two different simulators WFSA (which is a wellbore simulator) and TOUGH (which is a numerical code for the modeling of transportation of fluid, and heat in the reservoir) and also compared the results with the analytical approaches. For the analytical solutions, they used the conservation of energy and conservation of mass equations for two-phase flow for steady state condition.

Izgec et al. (2007) presented a study for developing transient wellbore simulator using semi-analytical temperature model. Their analytical temperature model is based on solving the energy balance equation for a differential length of the wellbore by considering convective heat loss into and out of the control volume and heat loss to the formation. They supported their model by applying several examples from gas and oil wells and verified the pressure and temperature computations with the field data.

Duru (2008) studied the distribution of reservoir and wellbore temperatures for different cases (single phase system, two phases system) by using the methods of operator splitting and adaptive time stepping. He also considered the flow dynamics such as Joule-Thomson heating (or cooling), adiabatic.

The pressure and temperature behaviors of geothermal wells in single-phase liquid reservoirs have been studied by Palabiyik et al. (2013). They focused on the characterization of reservoir by using both pressure and temperature data and developed a model for wellbore pressure and temperature. Also the sensitivity of temperature on different parameters such as conductivity, porosity, skin factor has also been considered. The study is based on 2D (r-z) fully implicit numerical model for investigation of the behaviors and sensitivities of pressure and temperature at production and injection points and observations points along the wellbore. Palabiyik et al.(2013) verified their model by comparing with a commercial thermal software PetraSim and obtained consistent results.

Kutun et al. (2014) worked on the temperature behavior of geothermal wells during production, injection and shut-in operations. They generally focused on the stabilization time of wellhead temperatures and developed a numerical model to observe the parameters effecting the stabilization time.

Akhlaghi et al. (2015) studied the effect of underground convective flows on the performance of ground heat exchanger systems by solving the energy balance equations under steady state.

As mentioned before, the aim of this study is to model the temperature behavior in the wellbore. In the following section the details of the developed model are given.

2. THE MATHEMATICAL MODEL

In this section we give the details of the mathematical model used in the study. As mentioned earlier the model is based on solving the energy balance equation considering steady state flow of fluid in the well. The energy balance equation is solved numerically for the system given below.

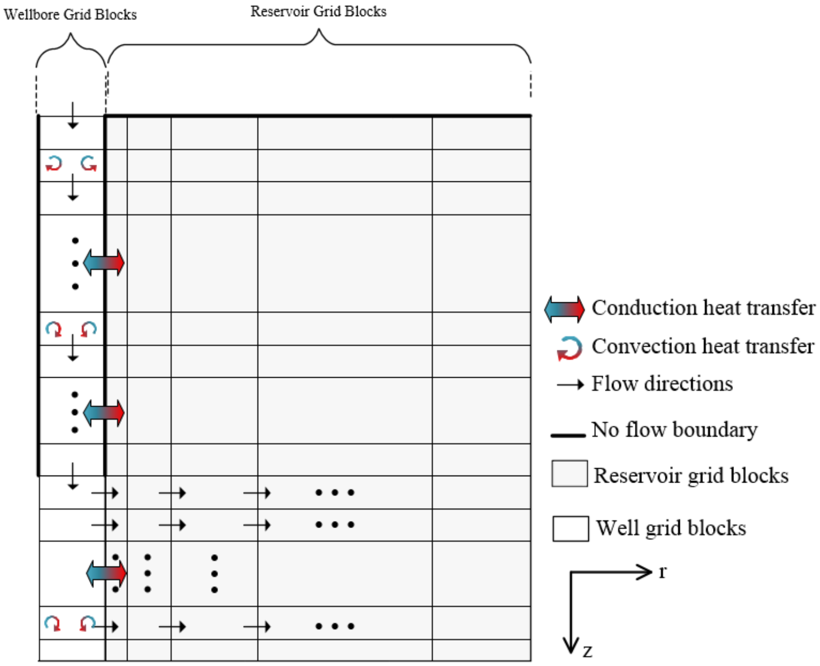

Figure 1: Sketch of the grid system use in the study.

As can be seen in Figure1, the system consists of two different grid block types. These are the well blocks and the formation grid blocks. To distinguish the grid blocks from the others, different parameter values have been used. For the well, porosity values are assigned as 1.

Any grid block i in Figure 1 is illustrated below in more detail. As can be seen in Figure 2, grid block i (for i= 1,2,…,N_t) has the following parameters: V_{bi}, ϕ_i, T_i, p_i and makes arbitrary number of connections with other grids where the total number of connections is represented by N_{ci} and any connecting grid is referred to j_l, for l= 1,2,…,N_{ci}.

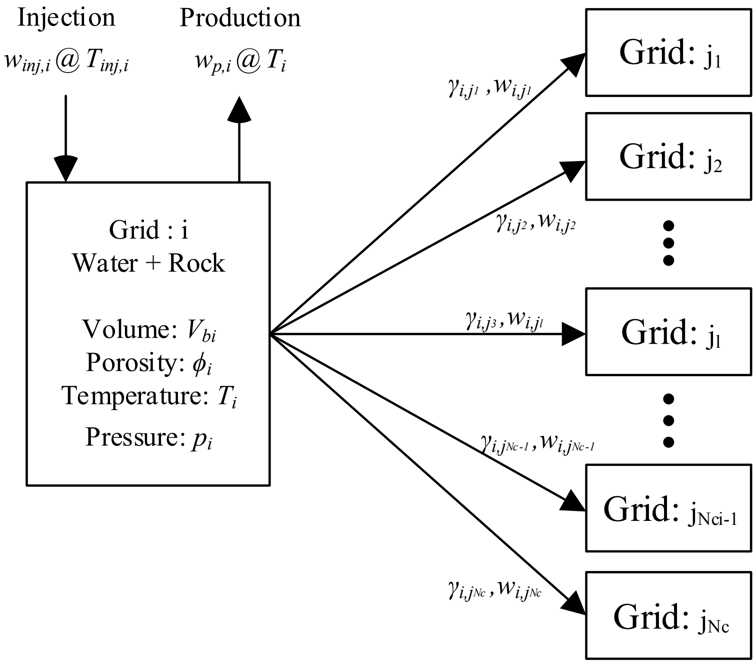

Figure 2: Schematic of a representative grid i for the lumped parameter model.

In Fig. 2 $w_{inj,i}$ is the mass flow rate of injection, $T_{inj,i}$ is the temperature of injected fluid; $w_{p,i}$ is the mass flow rate for the production, $T_{,i}$ is the temperature of grid i. Finally, w_{i,j_l} is the mass flow rate to and from grid i to j_l.

Since the model also considers the heat transfer due to conduction, this is modeled using Equation 1 where $\gamma_{i,jl}$ is the conduction index stating the energy flux per unit temperature drop due to heat conduction, T_{jl} is the temperature of grid j_l, T_i is the temperature of grid i.

$$Q_{i,j_l} = \gamma_{i,j_l}(T_{j_l} - T_i) \tag{1}$$

According to Figure 2, the energy balance equation can be written in the following form for an isobaric, single-phase liquid water and solid rock system:

$$\frac{d}{dt}\left[(1-\phi_i)V_{bi}\rho_{m,i}C_{m,i}T_i + V_{bi}\phi_i\rho_{w,i}u_{w,i}\right] + w_{inj,i}(t)h_{w,inj,i}(T_{inj,i,t},t) + w_{p,i}(t)h_{w,i}(T_i,t) - \sum_{l=1}^{N_{ci}} w_{i,j_l}h_\xi - \sum_{l=1}^{N_{ci}} \gamma_{i,j_l}(T_{j_l} - T_i) = 0 \tag{2}$$

In the above equation, ϕ is the porosity (fraction), V_b is the bulk volume (m^3), ρ_m is the density of rock matrix (kg/m^3), C_m is the specific heat capacity of the rock matrix (J/kg-°C), ρ_w is the density of water (kg/m^3), u_w is the specific internal energy of water (J/kg), h_w is the specific enthalpy of water (J/kg). The relevant variables such as enthalpy, specific internal energy, density are calculated from the steam tables (IAPWS, 2007).

For the convection term, upwinding is needed and is performed as folllows;

$$h_\xi = \begin{cases} h_{w,i}(T_i,t) & \text{Flow from tank i to tank } j_1 \\ h_{w,j_l}(T_{j_l},t) & \text{Flow from tank } j_1 \text{ to tank i} \end{cases} \tag{3}$$

The terms on the LHS of Eq (2) are accumulation of energy in the rock matrix and liquid water, energy content of the injected water, energy content of the produced water, energy influx from connecting grids, and the energy influx due to heat conduction respectively (Tureyen and Akyapi, 2011).

The porosity change due to the change of temperature for an isobaric system is calculated with the following equation (Onur et.al.,2008);

$$\phi(T) = \phi_0(1 + \beta_r(T - T_0)) \tag{4}$$

In Eq (4), ϕ_0 is the initial porosity, β_r is the thermal expansion coefficient of the rock.

Since Eq. (2) is a non-linear ordinary differential equation, a fully implicit Newton–Raphson method is used to manage the non-linearity. A forward finite difference discretization scheme is used for the terms involving the time derivatives. The primary variables are set as the temperatures in the grids i where i =1, 2,...,N_t (Tureyen et al., 2011). A fully implicit approach is used.

3. SYNTHETIC APPLICATIONS

In this section several synthetic applications are provided to demonstrate the cooling procedure. The first example is the base case which shows the temperature distribution at the bottomhole of a geothermal well during and after a cooling operation. The following examples illustrate the effects of various parameters.

3.1 Base Case

For this case, the temperature distributions during injection period and the shut in period are modeled to illustrate a cooling operation. The injection / shut-in scheme is given in Figure 3. Injection is carried out for a duration of 0.25 days and then the well well is shut-in. Unless otherwise stated, the injection rate is taken as 25 kg/s. The grid system shown in Figure 4 is used where the well is represented by 20 grid blocks and the formation is represented by 200 grid blocks. The red grid block in the figure is the open interval to the reservoir, and since the aim of this study is modeling the temperature behavior at the bottomhole for cooling operation, all the calculations and plots are made for this block throughout the paper. The initial grid temperatures are calculated by using the geothermal gradient of 0.09 °C/m. The properties used in the model is given in Table 1.

Table 1: Well and reservoir properties for model

r_w, Well radius, m	0.18
r_e, Reservoir radius, m	1000
φ, Reservoir porosity, fraction	0.10
ρ_r, Rock density, kg/m^3	2600
C_r, Rock specific heat capacity, J/kg-°C	1000
β_r, Rock thermal expansion coefficient, °C^{-1}	0
k, Thermal conductivity of rock, J/m-s-°C	2.92
z, Depth of reservoir, m	2750
n_r, Number of grid blocks in r direction	10
n_z, Number of grid blocks in z direction	20
w_{inj}, Injection rate, kg/s	25
T_{inj}, Injection water temperature, °C	30
T_{surf}, Surface tempature, °C	20
α, Geothermal gradient, °C/m	0.09

In field applications in geothermal wells, almost all equipments, tools and chemicals have working upper limits for temperature. Since generally the reservoir temperature is higher than this limit, cooling operations must be performed. Therefore, the time to reach the limit temperature after a cooling operation is very important to model.

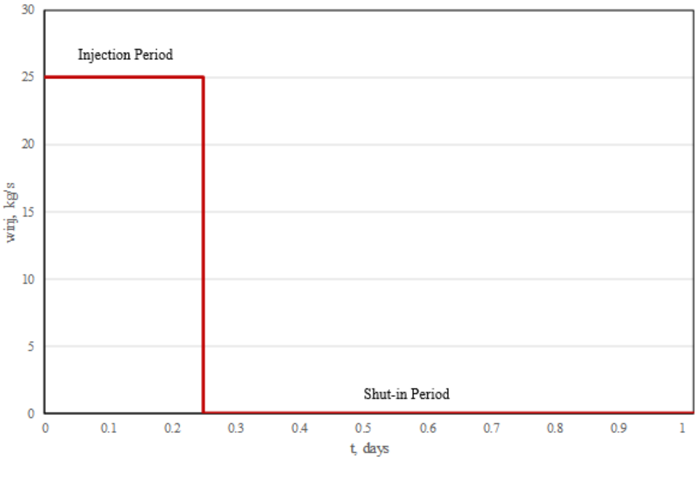

Figure 3: The rate scenario for the base case.

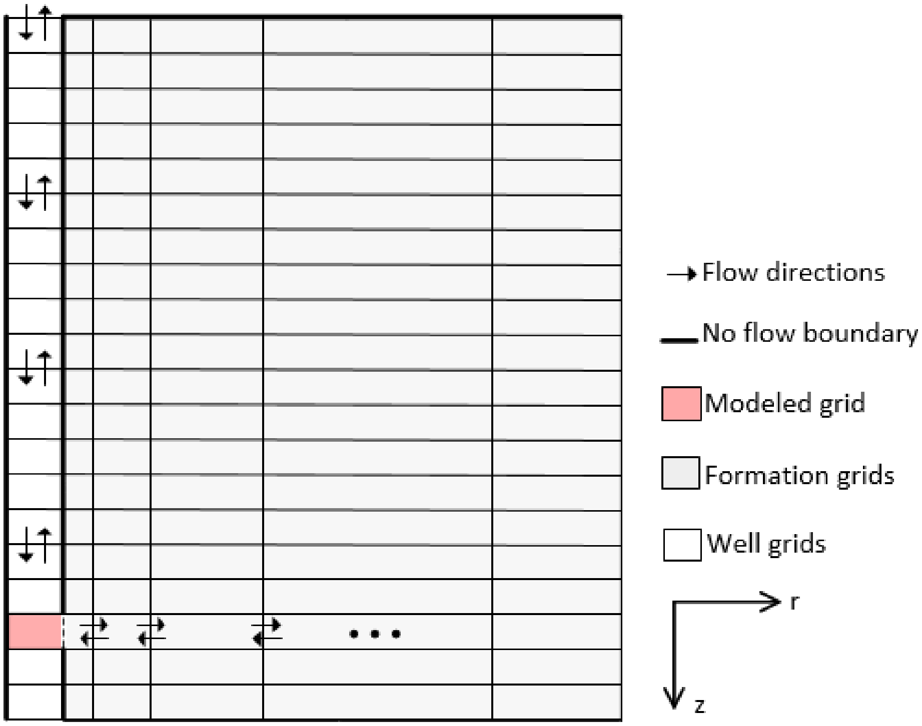

Figure 4: The sketch of the well and reservoir grid blocks.

Figure 5 illustrates the bottomhole temperature behavior for the injection / shut-in scheme given in Figure 3. As can be seen in Fig. 5, during the injection period, temperature is decreased from 245 °C to 57 °C in 0.25 days. For the shut-in section, temperature is increased up to almost 235 °C in 750 days. At around 1000 days, the original reservoir temperature is reached. It takes around 10 days for the temperature to reach 150 °C. If this temperature were to be taken as the upper temperature working limit for the tools and chemicals, then the operation would have to be completed in 10 days.

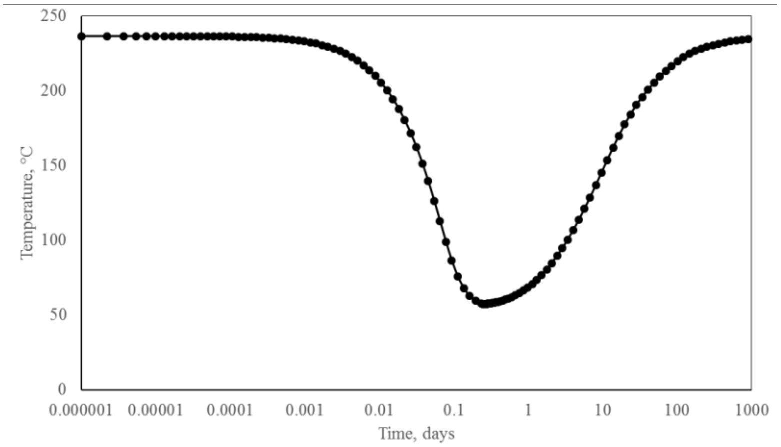

Figure 5: Temperature change by time at the bottomhole.

3.2 Effects of Various Parameters on the Time to Reach the Limit Temperature

In this section, the effects of various parameters on the duration to reach the limit temperature is studied. Additionally, the bottomhole temperature behavior during both injection and shut in periods are given for various parameters to provide a better understanding of the entire process. Some parameters can be arranged by the operators such as the injection rate, injection fluid temperature, where some are the reservoir related parameters such as the thermal conductivity of rock. The model is run separately by changing these parameters and the results are discussed. The working temperature limit is assumed as 200 °C for the following examples.

3.2.1 Effect of Injection Temperatures

To observe the effect of the injection fluid temperature, three different injection temperatures of 20 °C, 30 °C and 40°C are used while keeping all other parameters same as the base case mentioned in section 3.1. As is seen in Figure 6, after the cooling operation, temperatures are decreased to 53 °C (with an injection temperature of 20 °C), 59 °C (with an injection temperature of 30 °C) and 66 °C (with an injection temperature of 40°C) respectively from 245 °C. Figure 6 illustrates the overall bottomhole temperature behavior of the injection / shut-in process. As expected, when colder water is injected, the bottomhole temperature drops more at the end of the injection. Figure 7 illustrates the durations for reaching a limit temperature of 200 °C after shut-in. Because the bottomhole temperatures are cooled to a lower value when cooler water is injected, this results in longer times to reach the limit temperature.

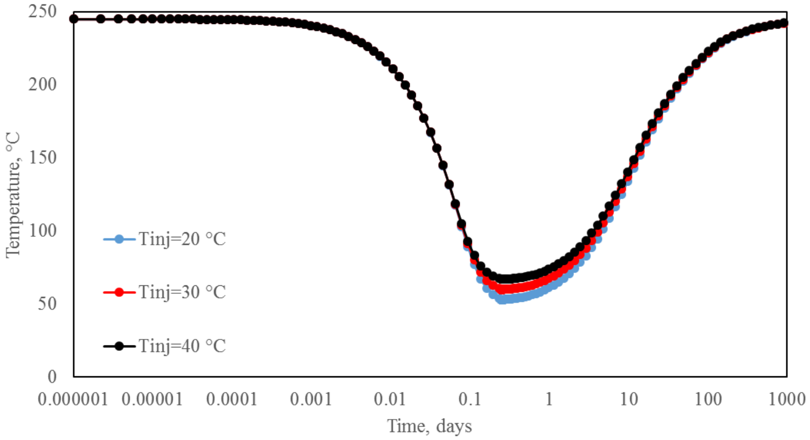

Figure 6: Temperature distribution for variable injection temperatures.

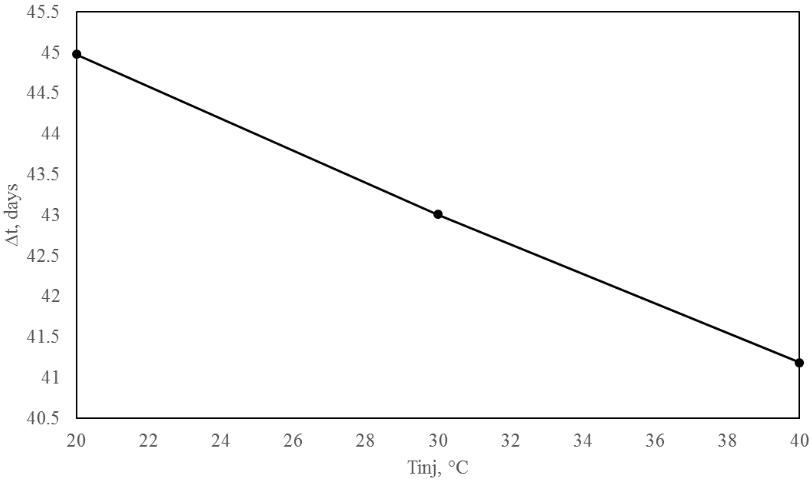

Figure 7: Time to reach the limit temperature versus injection fluid temperature

3.2.2 Effect of Injection Rates

To study the effects of injection rates, injection rates of 15, 25 and 35 kg/s are considered. Figures 8 and 9 illustrate the results. As can be seen in Figure 8, when higher production rates are used, this results in more bottomhole cooling. There are two main reasons for this. One is that using higher rates exposes the bottomhole to more cold fluids which naturally results in colder bottomhole temperatures. The second reason is that, as the rates are increased, this also results in an increase in the velocity of the fluid therefore reducing the heat losses to the surrounding formations as the water descends to the bottomhole. As illustrated in Figure 9, because the bottomhole is cooled more during the injection period, this results in longer times for reaching the temperature limit.

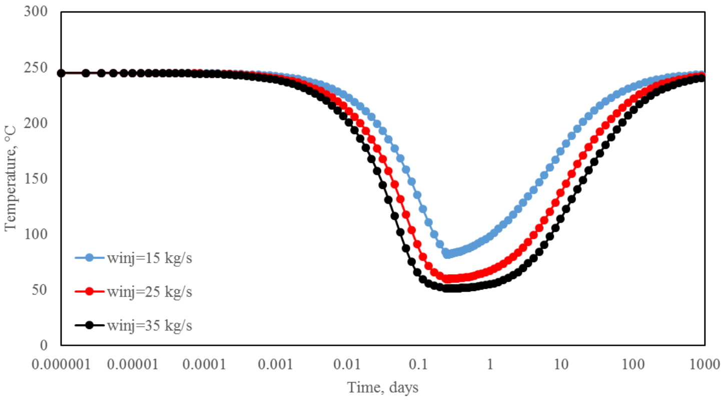

Figure 8: Temperature distribution for variable injection rates.

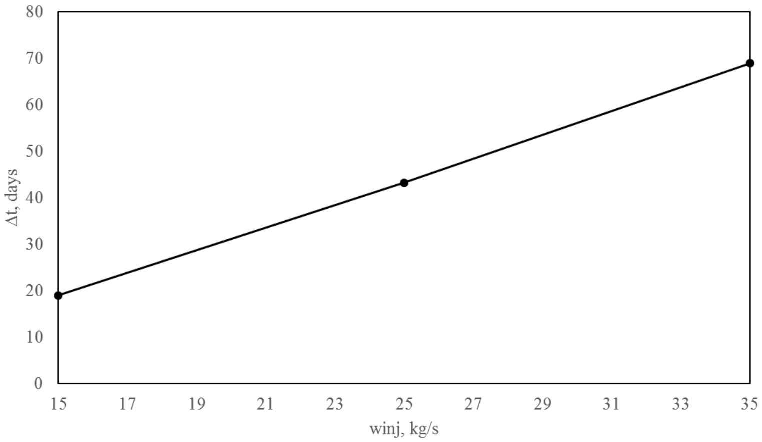

Figure 9: Time to reach the limit temperature versus injection rate.

3.2.3 Effect of Well Radius

Three different well radii are used for studying the effects of well radius on the cooling process. These are 0.1, 0.18 and 0.25 m. Figure 10 illustrates the results for the entire injection / shut-in scheme. As it is clear from Figure 10, when the radius is smaller, more cooling is observed. There are two main reasons for this. One is that even though the same flow rates are used, when the radius is decreased, the velocity of the fluid is increased and hence with the increase of velocity less heat is lost. The second reason is that when the radius is smaller, the area open to heat flow is also reduced which results again in less heat loss to the surrounding formations causing more cooling at the bottomhole. When the bottomhole is cooled more during the injection period, it takes more time to reach the limit temperature as illustrated in Figure 11.

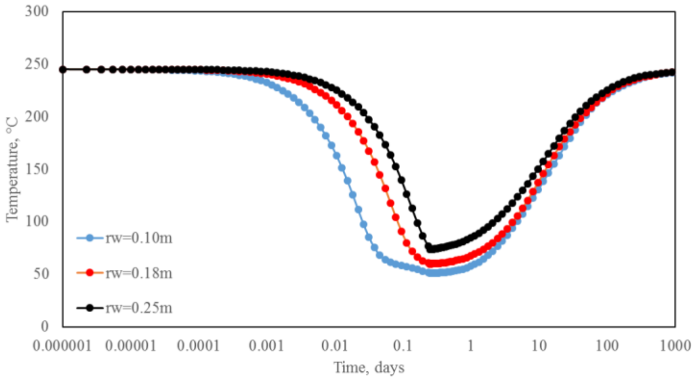

Figure 10: Temperature distribution for variable well radii.

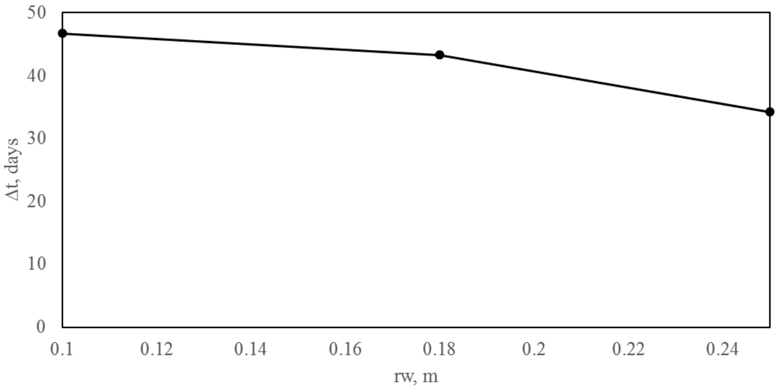

Figure 11: Time to reach the limit temperature limit versus well radii.

3.2.4 Effect of Thermal Conductivities of Rock

Thermal conductivity is one of the significant parameters for geothermal fields. Therefore, the temperature modeling for different values of thermal conductivities are studied to observe the effect on the temperature behavior. By keeping the other parameters same as the base case, the thermal conductivity values are considered to be 1, 2.92 and 4 J/m-s-°C. Since the higher conductivity value provides more conduction, more heat loss is observed during the injection and this results in less cooling. This is illustrated clearly in Figure 12. Figure 13 illustrates the time to reach the limit temperature. With lower rock conductivities it takes longer times to reach limit temperatures. This is expected because of two reasons. One is that with lower conductivities, the bottomhole is cooled more during the injection. The second reason is that, during shut-in, the only mechanism of heat transfer is by way of conduction since the fluid is still everywhere. Hence, lower conductivities cause a slower heat up of the bottomhole.

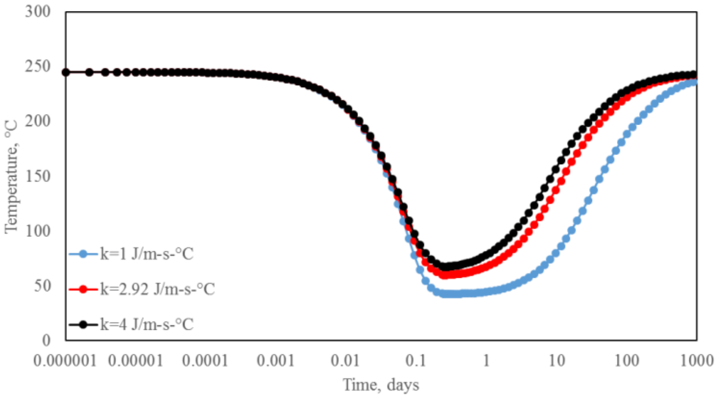

Figure 12: Temperature distribution for variable thermal conductivities of rock.

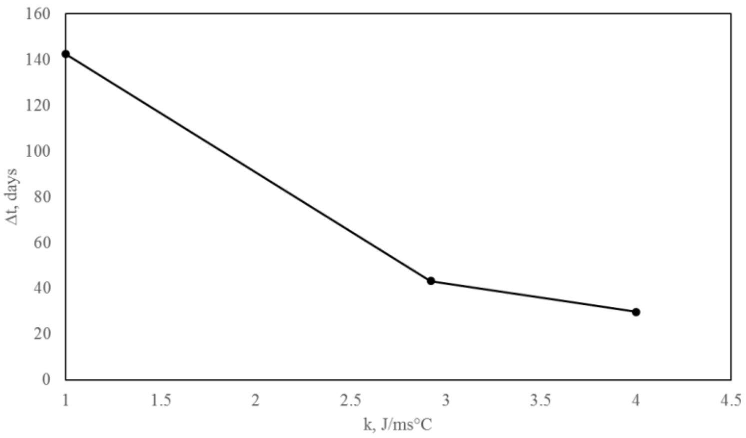

Figure 13: Time to reach the limit temperature versus thermal conductivity.

3.2.5 Effect of Injection Times

One of the parameters which can be arranged by the operator is the injection time. To study the effects of injection time, three different injection times are considered which are 0.15, 0.25 and 0.35 days. Since the injection rates are kept constant, the increase of the injection times provides more volume of injected fluid leading to more cooling at the bottomhole as illustrated in Figure 14. This leads to longer times to reach the limit temperature as shown in Figure 15.

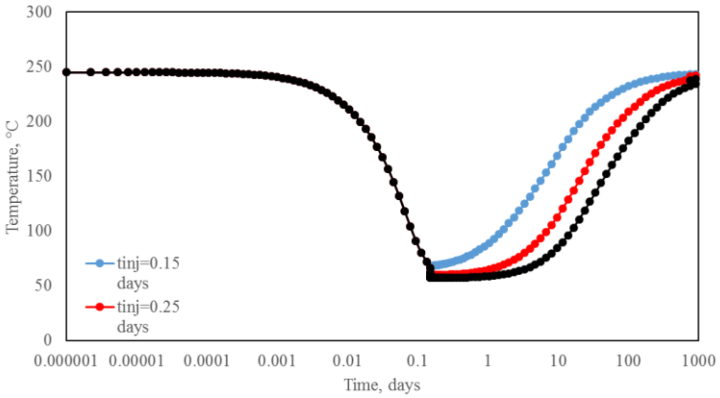

Figure 14: Temperature distribution for variable injection times.

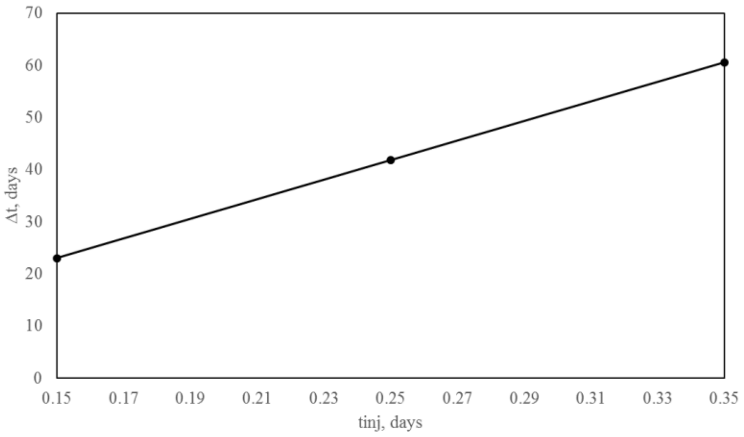

Figure 15: Time to reach the limit temperature versus injection time.

4. CONCLUSIONS AND FUTURE WORK

Various operations in geothermal fields require a cooling of the bottomhole to be performed due to the very high temperatures. In many cases, it is very crucial to be able to model accurately the cooling process using mathematical models. This study focuses on the cooling of the bottomhole and the effects of various parameters are studied. The following conclusions have been obtained from this study:

- A numerical model is developed for modeling the cooling of the bottomhole by way of cold water injection. The developed model is capable of simulating the cooling and the heating during the shut-in period right after the injection period.
- After the bottomhole is cooled, during the shut-in period the only mechanism that is present for heating the bottomhole is heat transfer by way of conduction.
- Using lower injection temperatures results in slower heating of the bottomhole during the shut-in period, since during the injection period the bottomhole is cooled more.
- Using low injection rates results in less cooling since the bottomhole is exposed to less cold fluids and heat losses to the surrounding formations are increased. This leads to faster heating of the well during the shut-in.
- The well radius has an effect such that when smaller well radii is used, this increases the velocity and decreases the heat loss to the surrounding formation leading to a more effective cooling. This results in larger heating times during shut-in.
- As expected, when the formation conductivities are low, this results in more cooling during the injection and longer heating times during shut-in.
- The effects of injection times is such that when injection is carried out for longer times, the bottomhole is exposed to more cold water. This results in more cooling of the bottomhole and a longer heating time during shut-in.

The results presented in this study are preliminary results. The model developed needs yet to be verified with existing models in the literature. If possible, real field data should be used to validate the results obtained in this study.

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