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Effect of Injected Cold Water on the Bottomhole Temperature Behavior

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ABSTRACT

Modeling bottomhole temperatures in geothermal wells is very important since in many cases it is almost impossible to measure directly the bottomhole temperature. Hence, an accurate mathematical model becomes a necessity for modeling the temperature behavior. Geothermal reservoir temperatures in Turkey, which are mostly located in the Buyuk Menderes Graben, can reach well over 250 °C. At these temperatures, some operations become impossible and a cooling schedule by way of injecting cold water is applied. Hence, the models used should be able to determine the behavior of the bottomhole temperature during the cooling and the heating after the cooling operation. During the injection process the injected fluid penetrates into the reservoir, hence during the cooling and heating that follows, this has to be taken into account.

A numerical model is developed for this purpose and is compared to the analytical approaches in the literature. Particularly the study focuses on the effect of the injected cold water, that has penetrated into the reservoir, on the cooling and the heating stages. The analytical approaches in the literature usually do not consider the effect of the colder water injected into the reservoir. The numerical model considers the heat transfer by way of conduction from the well to the formations and the convective heat transfer in the well and in the reservoir. Results show that the injected water in some cases can have an important effect on the bottomhole temperature behavior.

1. INTRODUCTION

The significance of the geothermal energy is becoming more and more observable by time. Renewable energy sources are becoming more popular everyday. According to Annual U.S. & Global Power Production Report, (Geothermal Enerygy Association, 2016), the global geothermal power industry brought online around 13.3 GWe of capacity in 2015. It is also stated that “According to GEA data collection, there is over 200 GWe of conventional hydrothermal potential globally available based on current knowledge and technology”. As it is understood from these numbers, there is lot more work to be done for geothermal energy.

Since the oil and gas industry is very advanced and widespread compared with geothermal industry, the companies are using similar techniques with oil and gas wells. However, due to the very high temperatures in geothermal wells, there are lots of tools, techniques and procedures adopted to high temperatures including temperature resistant chemicals. Besides these, to be able to normalize the temperatures of the geothermal wells, generally a cooling operation is being performed before any process.

The main objective of this study is the observing of the results of the injection of cold fluid (or cooling) into the well and reservoir. On the contrary to conventional oil and gas reservoirs, the geothermal reservoirs are quite fractured with high permeabilities which results with excess loss zones. Therefore, the models in this paper are developed to compare the cooling results of the full injection into reservoir and circulation in the well. In other words, the models compare the cooling effects through the reservoir of conduction and convection in terms of heat flow. The general trend in the literature is assuming one of these flow mechanisms in the studies, so this paper would be one of the first comparison in terms of flow mechanisms.

One of the most known and used study belongs to Ramey (1962) for heat transmission problem. He discussed the estimation of the temperature of injection fluids, tubing and casing as a function of depth and time by considering a steady state condition. Wu and Pruess (1991) have been developed an analytical model for the determination of the wellbore heat transfer, which can be used for field predictions and reservoir simulations, and verified their solutions with Ramey’s model.

Another study for the flow model of geothermal brine in the well and reservoir is handled by Hadgu et al. in 1994. They used two different simulators WFSA (which is a wellbore simulator) and TOUGH (which is a numerical code for the modeling of transportation of fluid, heat in the reservoir) and an analytical approach for verification of their models.

Garcia et al. (1998) published one of the first studies, which works on the thermal effects of lost circulations during shut-period. They have developed a computer code, which deals with the transient convective heat transfer due to the lost circulation in the rock surrounding a well.

In accordance with the aim of study of Palabiyik et al. (2013), a non-isothermal reservoir simulator is developed based on the equations of mass and energy balance to be able to simulate both pressure and temperature behaviors of a single-phase liquid dominated geothermal wells. They have compared and validated the model with Petrasim. One of the most important conclusions of the study was that the wellbore temperature has most significant sensitivity to the rock thermal conductivity value in comparison with other parameters such as permeability, porosity etc.

Kutun et al. (2015) developed a numerical model based on both energy and mass balance equations for investigation of the parameters affecting static and dynamic temperature profiles. They have validated their model by using the analytical models of Ramey (1962) and Hagoort (2004). Additionally, they worked on the stabilization times by using the model. Same year, Akhlaghi et al. (2015) presented a paper covers the subject for the effects of the underground convective flows Ground Source Heat Exchanger Systems where the general trend of the literature was the considering of the only conductive heat transfer into the strata and convective heat transfer in the tubes. They have developed a numerical model, which shows the significant effect of the convective heat transfer of the underground water on the performance of GSHES.

As one of the recent studies, Duan et al. (2016) have modeled the initial formation temperature by considering the conductive heat transfer in the wellbore and formation and the convection effect of the groundwater in the aquifer by using Horner Method.

As mentioned previously, the aim of this study is to model the effect of injected cold water on the bottomhole temperature behavior. In the following section the details of the developed model are given.

2. THE MATHEMATICAL MODELS

This section includes the details of the mathematical model used in the study. First models are developed with a numerical model, and then an analytical approach is used for verification/comparison with the numerical model.

2.1 Numerical Model

The numerical model is developed based on solving the energy balance equation by considering a steady state fluid flow in the wellbore. Figure 1 represents the system, which is solved numerically by energy balance equation.

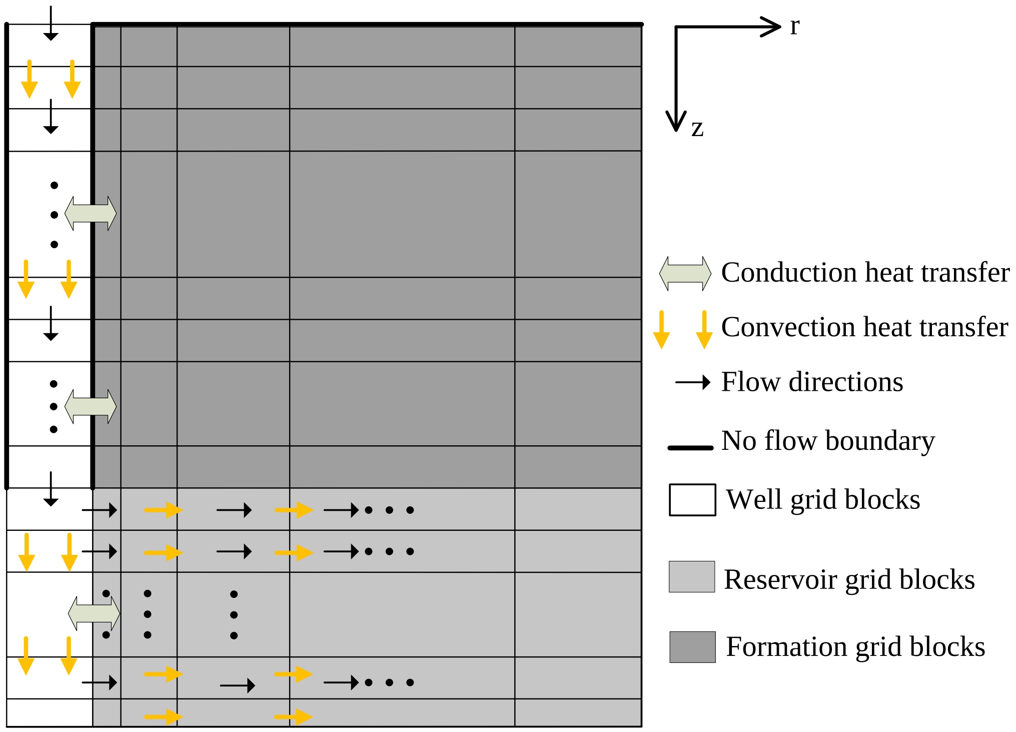

Figure 1: Sketch of the modeled grid system including well, tubing and reservoir.

Figure 1 shows three different grid block types which are well blocks, formation blocks and the reservoir blocks. It also shows the relative heat transfer mechanisms between blocks such as conduction heat transfer between the well and formation grid blocks. The differences between the grid blocks are determined by using different parameters such as porosity, density, thermal conductivities etc. For example, to be able to represent well grid blocks, the porosities are chosen as 1.

More detailed illustration of any grid block i in Figure 1 is given below in Figure 2. Figure 2 shows that any grid block i (for i= 1,2,…,N_t) having the following parameters: V_{bi}, ϕ_i, T_i, p_i, makes arbitrary number of connections with other grids. 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}.

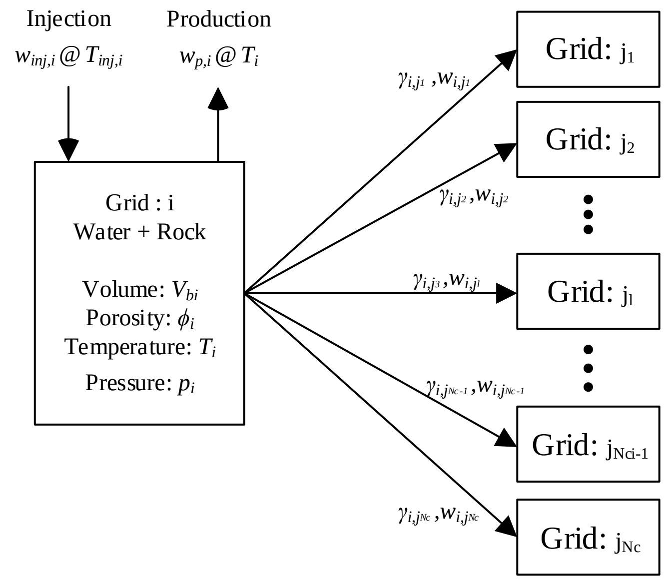

Figure 2: Schematic of a representative grid i for the lumped parameter model (Gurses, 2016).

In Figure 2 above, $w_{inj,i}$ represents the mass flow rate of injection (kg/s), $T_{inj,i}$ is the temperature of injected fluid; $w_{p,i}$ is the mass flow rate for the production (kg/s), T_i is the temperature of grid i (°C), w_{i,j_l} is the mass flow rate from grid i to j_l, T_{jl} is the temperature of grid j_l (°C), T_i is the temperature of grid i (°C).

The numerical model considers heat transfer in terms of both convection and conduction. The parameter for conduction heat transfer is representing by $\gamma_{i,jl}$ which is the conductance stating the energy flux per unit temperature drop due to heat conduction.

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

Energy balance equation for Figure 2 is given in the following form for single-phase liquid water and solid rock system:

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

The variables used in the Eq.2 are as follows; 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), $h_{w,inj,i}$ is the specific enthalpy of water (J/kg), h_w is the specific enthalpy of water (J/kg).

Enthalpy, specific internal energy and density are calculated from the steam tables due to the temperature and pressure (IAPWS, 2007).

The parameter for convection heat transfer is h_ξ which needs upwinding according to the neighboring conditions;

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

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. A similar equation has been used by Tureyen et al., (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 (fraction) and β_r is the thermal expansion coefficient of the rock (1/°C).

The energy balance equation stated in Eq. (2) is a non-linear ordinary differential equation. To be able to solve the non-linearity, a fully implicit Newton–Raphson method is used. 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 (Gurses, 2016).

2.2 Analytical Model

The analytical model is developed according to the study of Satman and Türeyen (2016). The approach is solving the heat balance in the wellbore by considering the single phase flow by assuming the heat flow in the formation is fully conductive.

For the analytical model, an injection period followed by a shut-in period is considered to represent the cooling operation. The following equation is used for the injection period (Satman, 2016);

$$T = T_{surf} + \alpha z - \alpha A + (T_{inj} - T_{surf} + \alpha A)e^{-\frac{y}{a}} \tag{5}$$

where T is temperature and is a function of depth (°C), T_{surf} is the surface temperature (°C), α is geothermal gradient (°C/m), A is a group of variables defined in Eq. 6, T_{inj} is the temperature of the injected fluid (°C) and y is the distance upwards from the bottom of the well.

$$A = \frac{wCf(t)}{2\pi k} \tag{6}$$

In Eq.6, w is mass flow rate which is injection rate here (kg/s), C is the thermal heat capacity of the fluid (J/kg-°C), k is the thermal conductivity of the formation (J/m-s-°C), and f(t) is a dimensionless time function representing the transient heat transfer to the formation.

There are couple of correlations of *f(t)* given by Ramey (1962, 1964), Ramey et al. (1981), Kutasov (2003), Kutun et al. (2015) and Hagoort (2004). Here Kutasov's (2003) correlation in Equation 7 and Kutun et al. (2015) correlation in Equation 8 are used for the injection period;

$$f(t) = 2\sqrt{\frac{t_D}{\pi}} \tag{7}$$

$$f(t) = \ln(1 + 1.7\sqrt{t_D}) \tag{8}$$

For buildup period the correlation of Kutun et al. (2015) in Eq.8 is used. In Equations 7 and 8, t_D is dimensionless time where it is defined with the following equation;

$$t_D = \frac{\kappa}{r_w^2} t \tag{9}$$

In the Eq.9, κ is thermal diffusivity of the formation (m^2/day), r_w is the radius of the well (m) and t is the injection time (day).

For the shut in period followed by the injection, the temperature distribution is calculating with the following equation (Satman, 2016);

$$T_{sh} = T_e + \frac{q}{2\pi k}\left[\ln\left(1 + 1.7\sqrt{t_{injD} + \Delta t_D}\right) - \ln\left(1 + 1.7\sqrt{\Delta t_D}\right)\right] \tag{10}$$

where T_{sh} is the shut in wellbore temperature (°C), T_e is the undisturbed formation temperature (°C), t_{injD} is the injection duration (day) and here Δt_D is the dimensionless time steps.

2.3 Verification of Numerical Model

To be able to compare and verify the analytical and numerical models, both models are run with the same parameters. The injection scheme is such that there is 10 days injection followed by a build-up period up to 1000000 days. Such a long time interval is chosen in order to observe the long term behavior. The parameters used for models are given in Table-1. The comparison results are given in Figure 3.

It is important to note that with the analytical model presented above, the bottomhole temperature is modeled in such a way that the heat loss to the formations are accounted for but the fluid does penetrate into the reservoir. In order to mimic such a behavior in the numerical model, the fluid is not allowed to enter the reservoir. Instead, the fluid is further down the well into the final grid block which is assigned a very large volume. The large volume is assigned so that the temperature will not change with time. In the following sections, cooling by way of circulation is also modeled in this manner.

Table 1: Parameters used for verification of models.

Parameters	Numerical Model	Analytical Model
w_{inj}, Injection rate, kg/s	20	20
T_{inj}, Injection water temperature, °C	30	30
T_{surf}, Surface tempature, °C	20	20
α, Geothermal gradient, °C/m	0.09	0.09
r_e, Reservoir radius, m	1000	-
φ, Reservoir porosity, fraction	0.10	-
ρ_r, Rock density, kg/m^3	2600	2600
C_r, Rock specific heat capacity, J/kg-°C	1000	1000
β_r, Rock thermal expansion coefficient, °C^{-1}	0	0
k, Thermal conductivity of rock, J/m-s-°C	2.92	2.92
z, Depth of reservoir, m	2000	2000
r_w, Well radius, m	0.18	0.18
C_w, Water specific heat capacity, J/kg-°C	-	3160
κ, Thermal diffusivity of the Formation, m^2/day	-	0.097

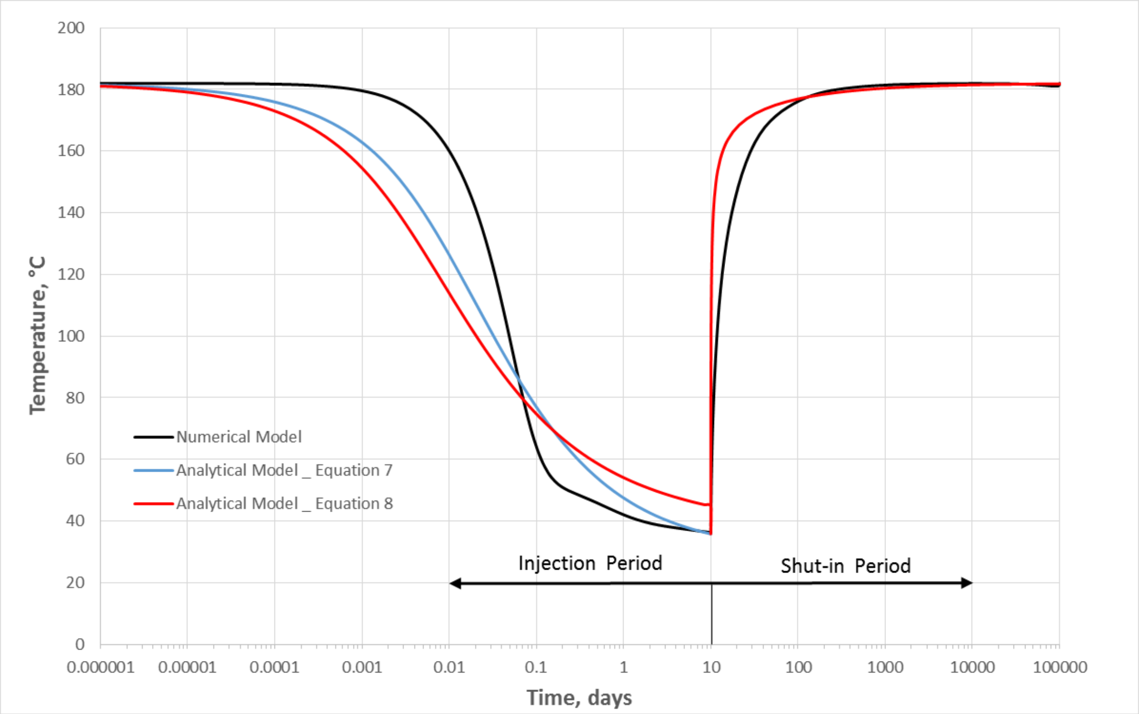

Figure 3: Comparison of analytical and numerical model.

The match between the behaviors of both models are considered to be acceptable.

3. SYNTHETIC APPLICATIONS

In this section, several synthetic applications are developed to demonstrate the temperature behavior through reservoir during and after the cold-water injection to a geothermal reservoir. The first case is given as “Base Case” with all parameters to be able to observe the effects of changing parameters individually in following cases.

3.1 Base Case

Synthetic models are developed to observe the effect of the injected cold fluid through reservoir in r direction as illustrated in Figure 1. Two main scenarios are considered and compared. In the first scenario, the cooling operation is conducted by way of injection into the reservoir. This is illustrated in Figure 4 (left). In the second scenario we consider the cooling only by way of conduction (mimicking a cooling by way of circulating the fluid). This is illustrated in Figure 4 (right). By comparing the behaviors of the two scenarios we aim to observe the effect of the injected water (into the reservoir) on the cooling of the bottomhole.

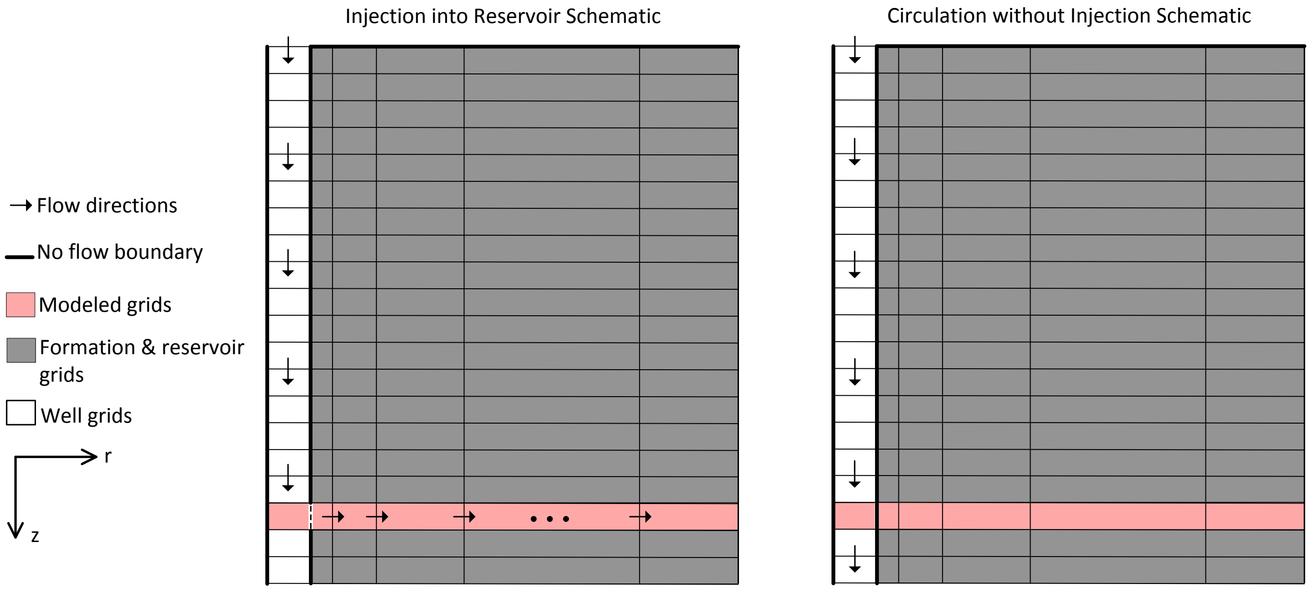

Figure 4: The illustration of the different modeling systems.

In the grid systems above, the well is represented by 20 grid blocks and the formation (reservoir) is represented by 600 grid blocks. To observe the effects and the differences of the “circulation without injection” and “injection into reservoir” models, temperature distribution in the red grid blocks in the figure above are plotted for different times. The general parameters used in the “Base Case” scenario are given in Table 2.

Table 2: 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	2000
n_r, Number of grid blocks in r direction	30
n_z, Number of grid blocks in z direction	20
w_{inj}, Injection rate, kg/s	20
T_{inj}, Injection water temperature, °C	30
T_{surf}, Surface tempature, °C	20
α, Geothermal gradient, °C/m	0.09

The rate scenario for the base case is given in Figure 5.

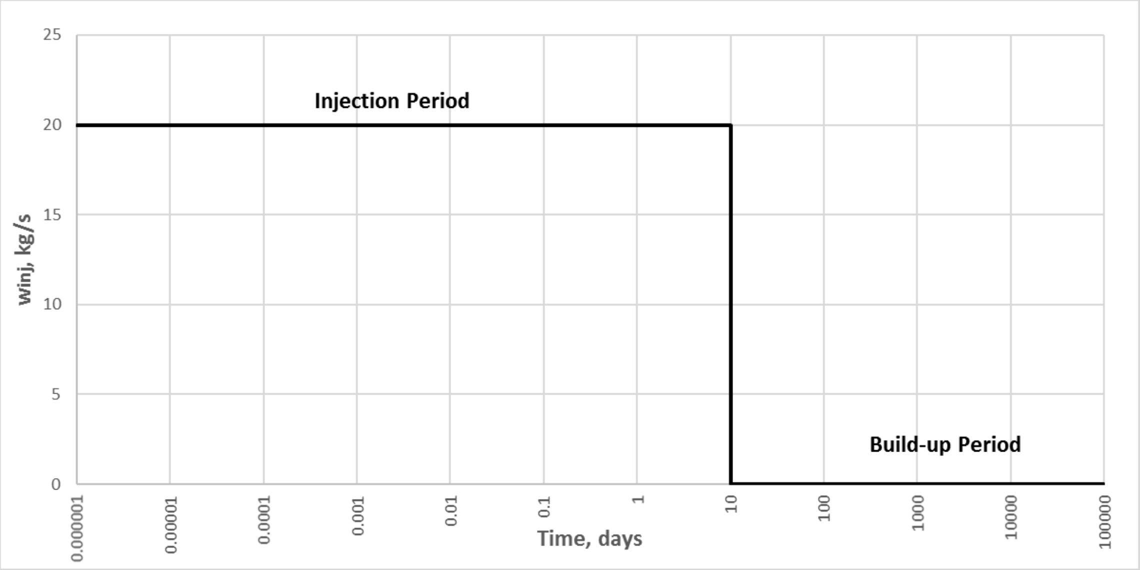

Figure 5: The rate scenario for the base case.

Figure 6 shows the temperature behavior of bottomhole for both models; "Circulation without injection" and "Injection into reservoir". During the injection period, both models are overlapping each other and giving the same behavior for bottomhole temperature. This is expected since the bottomhole temperature is affected most by the convective flow during injection. Weather the fluid is injected into the reservoir or circulated will not change the nature of the convective flow in the well. During the buildup period however, there is considerable change. The cooling performed by circulating the fluid builds up very rapidly whereas cooling performed by injection into the reservoir takes much more time. This is because in the injection case the reservoir has also cooled down up to a certain radius around the well.

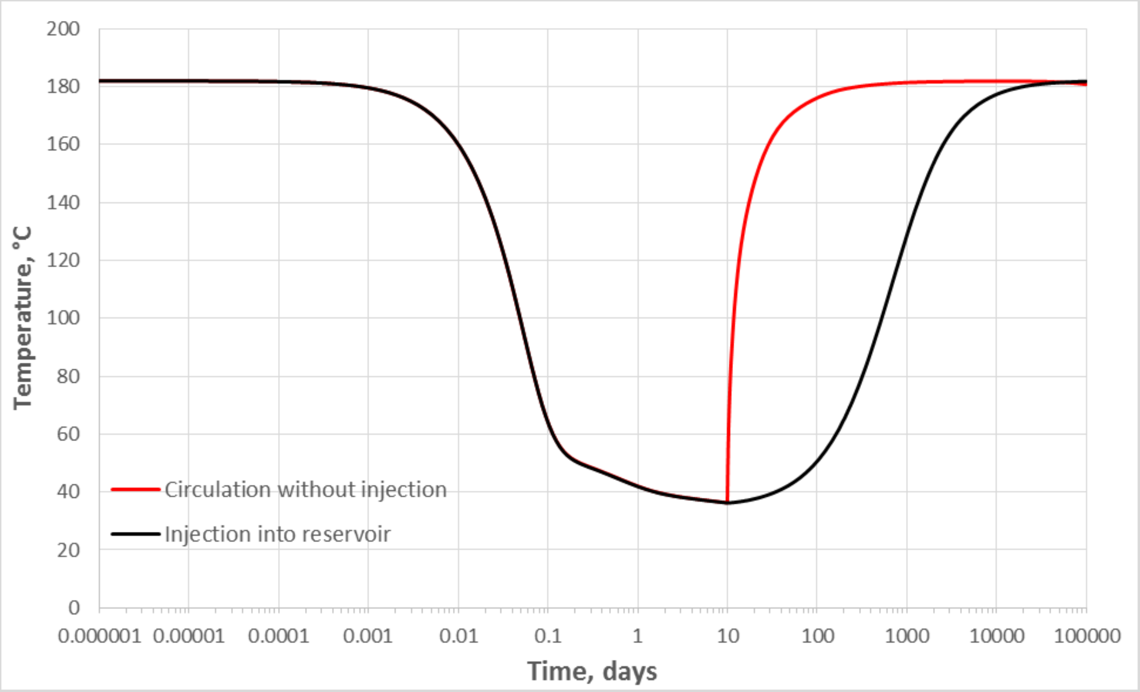

Figure 6: Bottomhole temperature behavior for the base case.

To have a better understanding of the phenomenon, we consider the temperature profiles in the reservoir at various different times given in Figures 7 and 8. Figure 7 gives the temperature profiles during the injection period and Figure 8 gives the temperature profiles during the buildup period for both scenarios of cooling; circulation without injection and injection into the reservoir. As expected, when cooling is performed by way of circulation, the temperature change region in the reservoir extend as much as about 2 m only. On the other hand when we consider cooling by way of injection into the reservoir, The region of change extends tens of meters into the reservoir. As a result, it takes more time for the temperatures to buildup for the cooling scenario of cooling by injection.

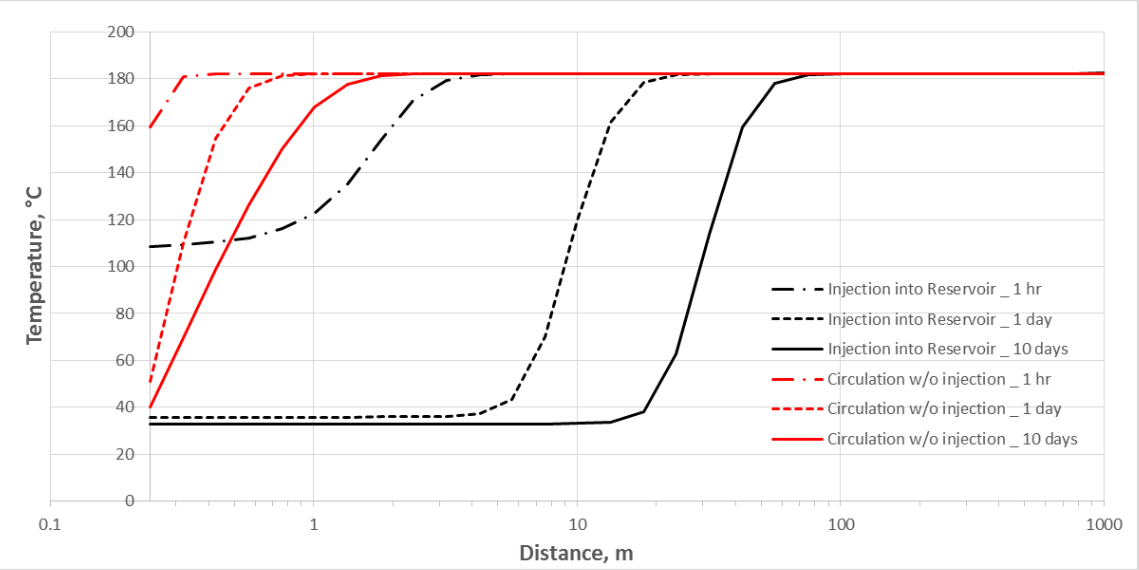

Figure 7: Temperature distribution in reservoir during injection period.

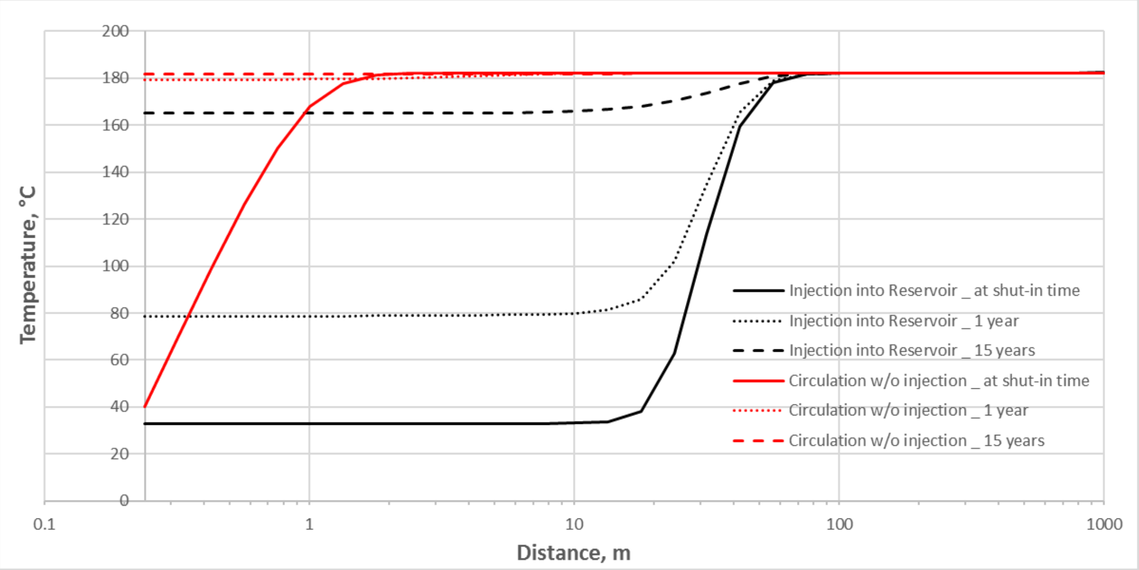

Figure 8: Temperature distribution in reservoir during build-up period.

3.2 Effects of Various Parameters During and After Injection on the Bottomhole Temperature Behavior

The effects of various parameters on the cooling and buildup behavior of temperature are investigated. The parameters that have been considered are the thermal conductivity, injection rate, injection time and injection temperature. Additionally, another case by changing two of the parameters (injection time and rate) at the same time is examined. Unless otherwise stated, the parameters are used same as the Base Case as shown in Table-2.

3.2.1 Effect of Thermal Conductivity

By keeping all other parameters the same as that of the "Base Case", the thermal conductivity values are changed and the effect on the bottomhole temperature is observed. Thermal conductivities are taken as 1.92 and 3.92 J/m.s.°C which was 2.92 for base case. Figure 9 illustrates the results. When Figure 9 is examined, there is no considerable difference between cooling by way of circulation and cooling by way of injection into the reservoir. This is expected since, as stated before, the cooling is dominated by convection. On the other hand, the buildup temperature is affected by the individual value of the thermal conductivity. As expected, with higher thermal conductivities, faster recovery of temperature is observed since the only means of heat transfer during buildup is by way of conduction.

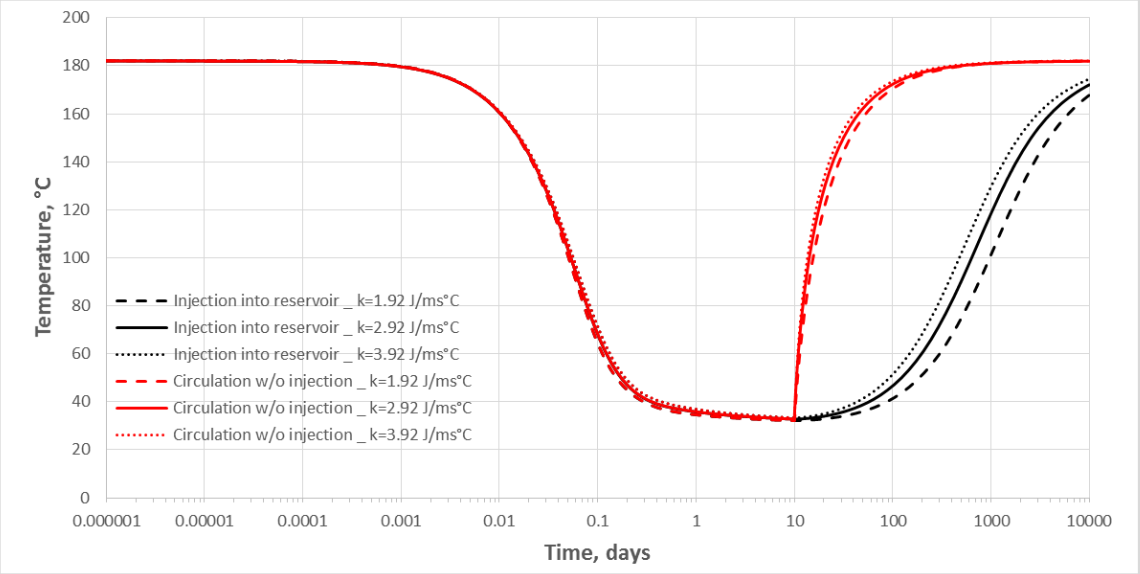

Figure 9: Bottomhole temperature behavior for various thermal conductivity values.

3.2.2 Effect of Injection Temperature

Figure 10 gives the effects of the injection temperature on the cooling and buildup of the temperature. As expected injection of cooler water results in more cooling at the end of 10 days. During the buildup period, if the cooling had been performed by way of circulation, then we do not observe considerable changes in the buildup temperature behavior for different injection temperatures. However, if the cooling is performed by way of injection into the reservoir, this considerably effects the buildup temperature behavior. During the buildup period when the cooling is by way of injection, the temperatures start at different values and this initially causes a large difference between the buildup temperatures. However, with time, this difference is minimized. This is again due to the fact that the buildup temperature is completely under the influence of conduction. If the buildup starts from a lower temperature we observe a faster buildup since there is more temperature difference which leads to more heat flow to the region of the cooled reservoir. If the buildup starts from a higher temperature, the buildup is slower because of the lesser heat transfer due to the lesser temperature difference.

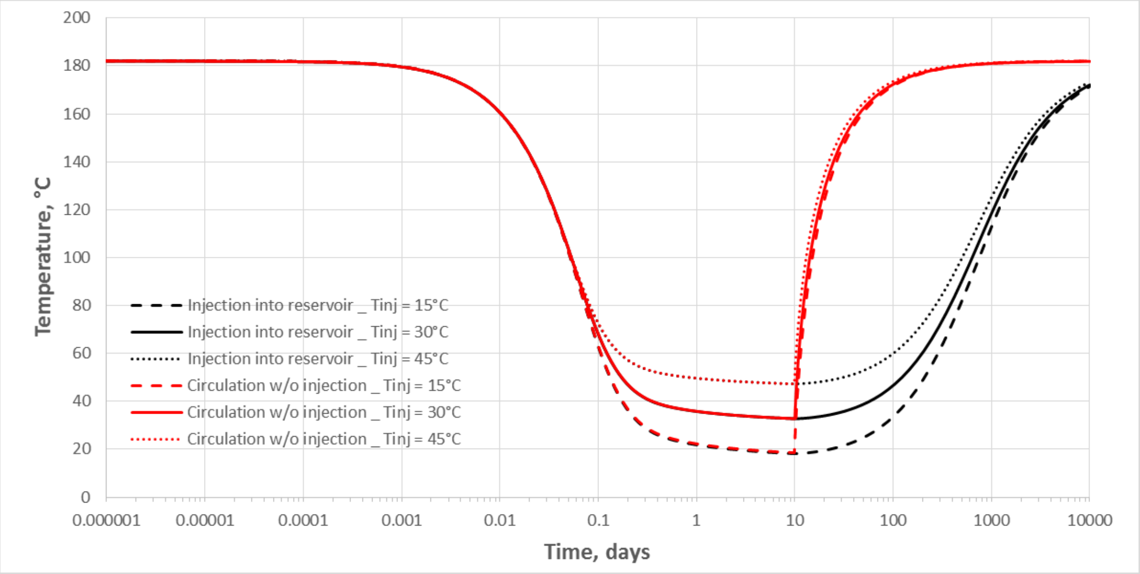

Figure 10: Bottomhole temperature behavior for various injection temperatures.

3.2.3 Effect of Injection Rate

Three different rates are considered in this subsection; 10, 20 and 30 kg/s. During the injection period different behaviors are observed for the temperature where the decreasing trend is different but eventually start to converge. This is because the converged temperature is dominated by the injection temperature. During the buildup no considerable difference is observed since the starting temperature for the buildup are all the same.

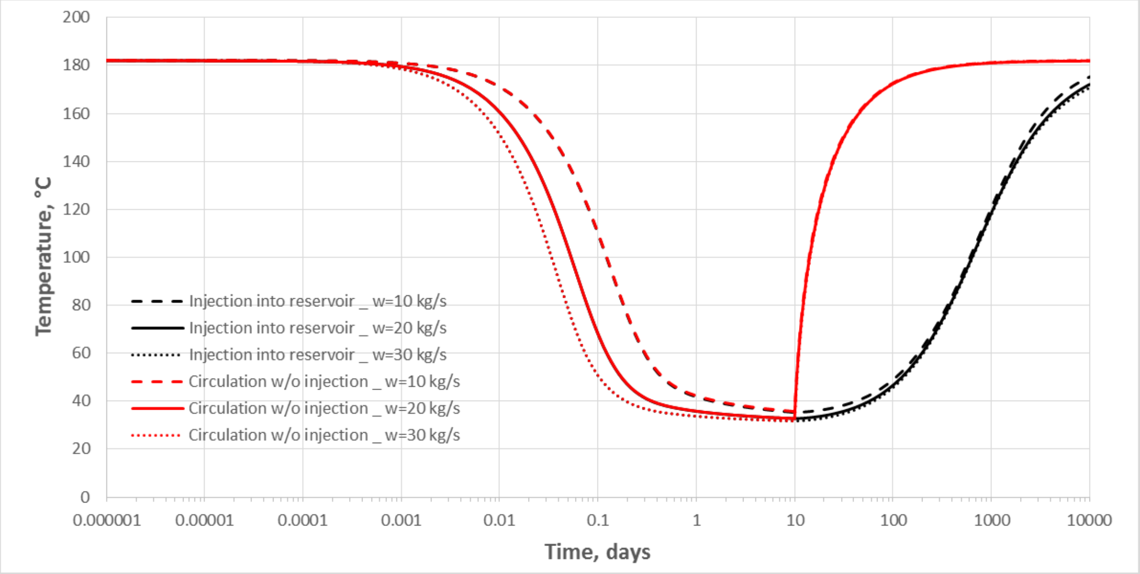

Figure 11: Bottomhole temperature behavior for various injection rates.

3.2.4 Effect of Injection Program

In this section we consider comparing the injection program. The aim is to test how the temperature profiles would change if the injection is performed slowly or in a fast manner. For this task, we keep the total injected amount of water to be constant and try three different rates with different injection periods given below:

- w_{inj} = 10 kg/s t_{inj} = 20 days
- w_{inj} = 20 kg/s t_{inj} = 10 days (Base Case)
- w_{inj} = 40 kg/s t_{inj} = 5 days

Figure 12 illustrates the results. A program with a higher rate and shorter injection time provides the most cooling. This is because during the injection less heat is lost to the surroundings. During the buildup, if the cooling is performed by way of circulation, there is a difference between the temperature behaviors since the starting temperature and time of the buildup is the same. However, we observe no difference if the cooling is conducted by way of injection into the reservoir. This is because No matter what kind of cooling program we use, the amount of water injected will always be the same and the same kind of radius occupied in the reservoir.

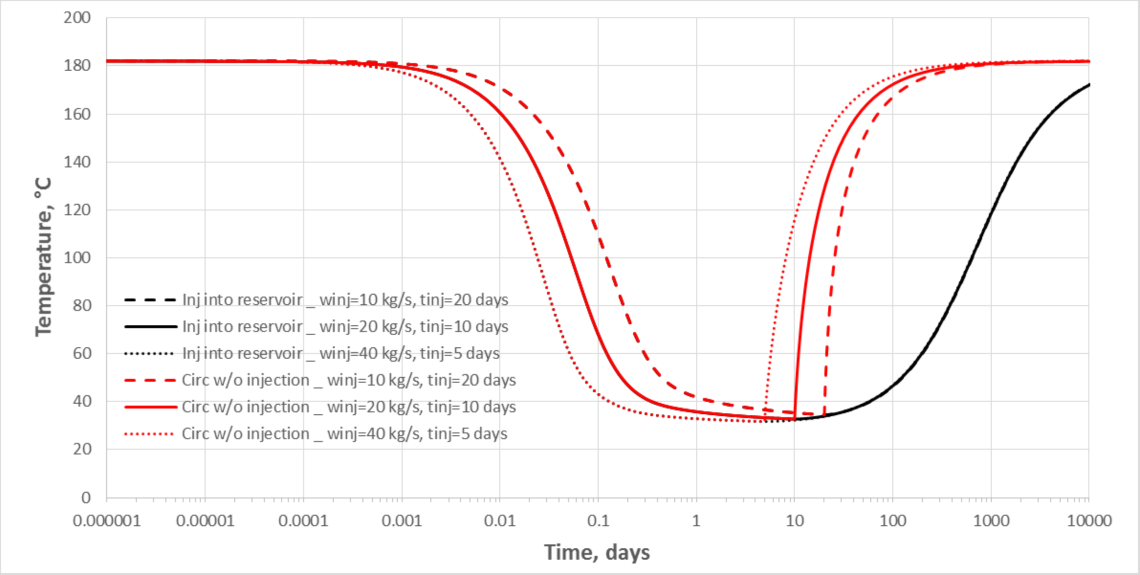

Figure 12: Bottomhole temperature behavior for various injection programs.

4. CONCLUSIONS

In this study we aim to compare two different bottomhole cooling schemes in geothermal reservoirs. The first is cooling by way of circulating the fluid in the well and the second is by way of injection into the reservoir. A numerical model is developed for comparing the two scenarios on a synthetic example. It is also important to note that many of the analytical approaches in the literature for modeling bottomhole cooling does not take into account the effects of the injected water. Here we show that the injected water can have a significant effect especially during the buildup of temperature.

The following conclusions are obtained from this study:

- No matter what the cooling scheme is (weather it is cooling by circulation or cooling by injection into the reservoir) the temperature behavior during the injection period is the same. The main reason for this is that during the injection period, heat transfer by way of convection dominates the temperature behavior.
- The cooling scheme affects considerably the buildup of temperature. This is because of the extended cooled region when the water is injected into the reservoir.

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