Uncertainty Analysis of Thermal Recharge by Free Convection in Geothermal Reservoirs

By

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in partial fulfilment of the requirements for the degree of

Bachelor of Science
in Applied Earth Sciences

at the Delft University of Technology,
to be defended publicly on Tuesday July 11, 2017.

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Abstract

This study investigates the thermal recharge of deep geothermal reservoirs by free convection. A coupled numerical model that is built in Comsol Multiphysics is presented in order to estimate the thermal recharge during the first 30 years of production from a typical high enthalpy geothermal reservoir. A sensitivity analysis was carried out to find which parameters have most significant impact on the thermal recharge by free convection and reservoir lifetime. The sensitivity analysis is mainly focussed on fault properties. The developed model consists of a reservoir with two confining layers and vertical faults. This model is used to calculate the produced energy, extracted energy from the reservoir and the recharge by conduction based on which the thermal recharge by free convection can be calculated. Results show that free convection is a significant part of the produced energy. Therefore, it is important to take free convection into account by estimating the recoverable energy. From the results can also be concluded that fault aperture, fault height, fault permeability and thermal conductivity of the confining layers have a significant impact on the thermal recharge by free convection of a faulted geothermal system. Fault density also has impact on the thermal recharge, but the relation between fault density and thermal recharge by free convection is less clear. Thermal conductivity of the reservoir rock has no impact on the thermal recharge by free convection according to the results of this model.

Acknowledgements

I would like to thank Nima Gholizadeh Doonechaly, who helped me a lot during this project.

1 Introduction

The production of geothermal energy has increased globally, due to the increasing demand of renewable energy. In some areas, the heat can be extracted easily as a result of elevated heat flows. Still, shallow reservoirs have often very low temperatures compared to deep reservoirs. In most cases, however, the permeability of deep reservoir rocks is not high enough, since the rock is very compacted. Therefore, fractures and faults form a very important part of the reservoir to create enough permeability.

Although geothermal energy is often seen as sustainable, any geothermal reservoir can be exhausted. Cold water is injected into the reservoir at the injection well to maintain the reservoir pressure during the lifetime of the reservoir. However, due to the injection/circulation of cold water, the reservoir will cool down (Ganguly & Mohan Kumar, 2012) until a point when the production temperature is below the profitable limit. (Bödvarsson & Tsang, 1982).

If the conditions are favourable, the reservoir can be recharged by the heat of adjacent formations during both the circulation as well as the shut in period. This process is called thermal recharge. Thermal recharge is dependent on many properties and processes, of which the two most important are conduction and free convection. Conduction can recharge the reservoir by the direct contact of hot adjacent layers to the cooled reservoir rock. Besides the direct conduction of heat into the reservoir, the heat of adjacent formations can also cause temperature, and thus density, differences within the fluid. This causes density-driven flow mainly within faults and fractures, which can enhance the recharge of the reservoir. The described process is called free convection. The density-driven flow does need a certain permeability. Therefore, free convection in deep reservoirs cannot be through porous media because the permeability is too low. Faults on the other hand, can have significant impact. An accurate prediction of thermal recharge is very important to estimate the economic lifetime of the reservoir as it may significantly contribute to the partial thermal recovery of the reservoir during the fluid circulation. The current study focuses mainly on the recharge during the circulation period.

Research on thermal recharge dates back to the 1970's. Muffler and Cataldi (1978) investigated the extent to which a geothermal reservoir can be resupplied with heat. They found that if the geological circumstances are advantageous, the reservoirs can be partly recharged. Murphy (1979) was the first to study the effect of free convection in fractures and faults on the behaviour of the reservoir. The results show that free convection is not only influenced by the fluid itself, but also by the adjacent rock mass. After a linear stability analysis, he found that the strength of convection increases with Rayleighs number. Gringarten (1987) studied the recovery potential of geothermal reservoir by making simple models to evaluate the heat exchange between the reservoir and surrounding formations. He concluded that the production scheme has great influence on reservoir lifetime and recovery of the reservoir. In addition, it was found that the heat recovery factor increases by the reinjection of cold water. Murphy's results were extended by Tournier et al. (2000) by developing a numerical model to investigate the convection in the fracture plain, as well as the conduction inside the fracture wall. Yet, this research is not applied to the recharge of geothermal reservoirs. Mégel and Rybach (2000) performed long-term calculations regarding the effect of the reinjection of cold water. Their conclusions improve Gringartens results by finding that optimal results can be achieved by short production cycles. Diersch and Kolditz (2002) did an extensive study about free convection and transport in porous media. The study included convection systems, balance equations, phenomenological laws, and temperature depended relations for density and viscosity. For the resulting nonlinear problem, a numerical method was presented. One of their conclusions was that heterogeneity is a key factor in the modelling of simulating variable density flow. Besides that, the modelling of variable density flow is very complicated and require complicated numerical meshes. Therefore, efficient and accurate solving methods are necessary. Rybach (2003) investigated the renewability of geothermal energy and found that it can indeed be called renewable, because of the relatively low recovery period and minor environmental impacts. Coumou et al. (2008) made 3D numerical simulations of hydrothermal systems in the sub-seafloor in order to understand the structure and transient dynamics. They were able to simulate the convection flow patterns, which ensure optimal heat transfer. Bataillé et al. (2006) was the first to apply the knowledge about free convection in fractures to the heat production of an Enhanced Geothermal System. Free and forced convection were modelled in a numerical study considering a large range of Rayleighs numbers and injection rates. Results of the study show that free convection is a very important factor in exploitation, without which the economic lifetime of a reservoir will dramatically decrease. In the study of Graf and Therrien (2008) and Graf and Therrien (2009) a test case is developed for three-dimensional density-driven flow, to help by the developing of other variable-density flow models. Besides that, a stability analysis is performed on a series of density-driven flow simulations. The main purpose of this study is to make a guideline for the predicting of stability of geothermal systems. In another study, O'Sullivan et al. (2010) also concluded that geothermal systems are renewable on the long term. Despite the fact that in almost all systems the heat extraction exceeds the heat recovery, the reservoirs will recover fully after a certain period of a non-production. Fox et al. (2013) used an analytical approach to estimate the renewability of EGS reservoirs. In their approach, they modelled thermal conduction in a reservoir containing one rectangular fracture, and compared it with numerical simulations of a reservoir with multiple fractures. The results show that multifractured systems have a bigger capacity to remain high production temperatures.

Since 2015, the number of research investigations about geothermal energy increased rapidly. Poulsen et al. (2015) investigated the influence of surrounding layers on the sustainability of the geothermal reservoir. The authors analysed the sensitivity of the thermal recharge to the production rate, injection rate, reservoir thickness and thermal conductivity of the confining beds. They found that the production profile is highly depending on the thermal conductivity. Tureyen et al. (2015) developed a simplified model to examine the productivity of both unitized and non-unitized reservoirs. Results of their study confirmed the previous counterparts that natural recharge has significant impact on the average reservoir temperature. Furthermore, it was shown that unitized production contributes to a more complete heat recovery of the reservoir. Leary et al. (2015) looked in detail to existing natural flow systems. They concluded that drilling costs could be reduced by the precise mapping of spatially correlated fracture systems and locating the large-scale permeability pathways in a reservoir. Scott et al. (2015) reported a numerical model of the transient fluid flow in high-enthalpy geothermal systems. In this model, they included non-linear changes in temperature- and pressure-dependent fluid properties. The results are consistent with observations, and are an indication that these kind of hydrological models can be used in furture geothermal projects Crooijmans (2016) also developed a model to study the influence of heterogeneity on the lifetime and recovery of a geothermal reservoir. A positive relationship was found between heterogeneity and both recovery and lifetime. Scott et al. (2016) reported numerical simulations of heat transfer and fluid flow around magmatic intrusions to find important features in thermal and hydraulic structures of geothermal systems. One of their findings was that systems with high permeability show near-isothermal upflow and boiling at depths greater than 1 km. Shanchez-Alfaro (2016) performed a mineralogical, physical and chemical analysis of a geothermal reservoir in the southern Andes. The results show that the combination of brittle deformation and heat-fluid-rock interaction is very favourable for this reservoir. Su et al. (2017) studied the heat recovery period of an enhanced geothermal system by using a fixed multi-parallel fracture set in the model. In their study, conductive heat transfer was considered as main recharge process. Results suggested that the two factors—which mostly affect the thermal recovery—are initial temperature and recovery time, which is in consistent with the results presented by Poulsen (2014).

The purpose of this study is to investigate the thermal recharge of deep geothermal reservoirs, in particular, by free convection. A coupled hydro-thermal numerical model is built in Comsol Multiphysics in order to calculate the thermal recharge during the first 30 years of energy production (circulation). A sensitivity analyses is carried out to find which parameters have most significant impact on the thermal recharge by free convection and the production and the reservoir lifetime. Because in low permeable reservoirs, free convection is highly dependent on faults' attributes, the sensitivity analysis will be mainly focused on fault properties.

2 Methodology

2.1 Fluid flow

Fluid flow in the reservoir is defined by using the model Darcy's Law of Comsol Multiphysics. This module describes fluid movement trough porous media. The main equations used in this part is equation 1 in which u is calculated by equation 2.

$$\frac{\delta}{\delta t}\left(\varepsilon_p \rho\right) + \nabla * (\rho u) = Q \quad (1)$$

$$u = -\frac{\kappa}{\mu}(\nabla p + \rho g \nabla D) \quad (2)$$

Where ε is porosity (-), ρ is density (kg/m^3), u is the velocity vector (m/s), p is pressure (Pa), t is time (s), μ is viscosity in (Pa*s), D is the diffusivity (m^2/s) Q is the flow rate (m^3/s), g is the gravitational constant (m^2/s) and κ_{eff} is the effective permeability (m^2). Pressure plays a very important role in the calculation of flow. Because pressure in the subsurface is varying over depth, the pressure is defined as 1000 Pascal per meter depth to represent the hydrostatic pressure regime.

In the case of a geothermal reservoir, there are two main fluid movement mechanisms: Free and forced convection. Free convection is caused by the fact that the density of fluid is changed by temperature. Different parts of the reservoir undergo temperature changes during production, because of the reinjection of cold water and the heating of adjacent formations. The water within the reservoir, will therefore change in density. Free convection is taken into account in the calculation of the velocity vector in equation 2. The gravitational constant used in this equation, causes the upward flow of heated water due to density differences.

Forced convection is the forced movement of fluids through the porous medium. In this case forced convection is caused by the pumping of warm water at the production well, and the reinjection of cold water at the injection well. This effect is also taken into account in the velocity vector by the pressure differences. The inward and outward mass flux is defined by equation 3.

$$N = \frac{Q}{A} \quad (3)$$

In which N is the inward or outward mass flux (kg/(m^2*s)), Q is the injection and production flowrate, which is defined as 175 kg/s and A is the area of the production or injection well (m^2). called

2.2 Heat transfer

Heat transfer is taken into account by using a module of Comsol Multiphysics Heat transfer in Porous media. This module combines conduction in a porous domain, and the fluid within the domain. The transient temperature distribution is created by solving equation 4 in which q is calculated by equation 5 and u is calculated by equation 2.

$$(\rho C_p)_{eff}\frac{\delta T}{\delta t} + \rho C_p u * \nabla T + \nabla * q = Q \quad (4)$$

$$q = -\kappa_{eff}\nabla T \quad (5)$$

Where ρ is density (kg/m^3), C_p is specific heat capacity (J/(kg*K)), T is the absolute temperature (K), q is the heat flux by conduction (W/m^2), t is time (s), u is the velocity vector (m/s), Q is the heat source (W/m^3) and κ_{eff} is the thermal conductivity (W/m*K).

Because during production the temperature distribution is influenced by the movements of fluids, the energy transported by the fluid has to be taken into account in the heat transfer module. The module is able to model this influence of forced and free convection. This is due to the use velocity factor u (eq. 2) in the heat transfer equation (eq. 4). In the velocity factor free convection is taken into account by the gravitational constant and forced convection by the pressure differences.

3 Thermal Recharge Estimation

The production temperature and average reservoir temperature were calculated during 30 years of production. Thermal recharge is defined by the following balance (Poulsen, Balling, & Nielsen, 2015):

$$E_t = \Delta E + E_p \quad (6)$$

In which ΔE is the change in energy content of the reservoir (J) and E_p is the time integrated extracted energy from the production well (J). ΔE and E_p are calculated by using the following formulas.

$$\Delta E = \iiint \rho_{res} * Cp_{res} * (T_{avgres} - T_{avginit})\ dV_{res} \quad (7)$$

$$E_p = \iint \int_0^t \rho_{brine} * Cp_{brine} * (T_{prod} - T_{inj}) * v_{fluid}\ dt\ dS_{well} \quad (8)$$

Where ρ is the density (kg/m^3), Cp is the heat capacity (J/(kg*K), T is temperature (K), V is volume of the reservoir (m^3), v is velocity of the fluid at the wellbore (m/s), S is the surface area of the well (m^2).

Thermal recharge of the reservoir is dominated by two main mechanisms: conduction of heat from surrounding layers through the layer boundaries, and free convection in faults. Conduction through these boundaries can be defined by calculating the heat flux over the boundaries between the reservoir and the confining layers. The effect of free convection is assumed to be the other part of the calculated thermal recharge. This paper will focus on the effects of free convection in faults. This leads to the final equation for thermal recharge by free convection:

$$E_{t\_conv} = \Delta E + E_p - E_{cond} \quad (9)$$

In which E_{t_conv} is the thermal recharge by free convection (J), and E_{cond} is the conductive energy from surrounding layers through the layer boundaries (J).

4 Model Setup

4.1 Model parts

The reservoir is simulated by a rectangle with its centre at a depth of 3650 m, which is a typical depth for deep geothermal reservoirs in the Netherlands. The width and length of the reservoir are 1000 meters and the thickness is 300 meters. Two wells are placed with a distance of 667 m away from each other. The wells have a length of 200 meters. A wellbore size of 8.5" and a skin factor of -1.35 is used. The geometry of the reservoir without faults is shown in figure 1.

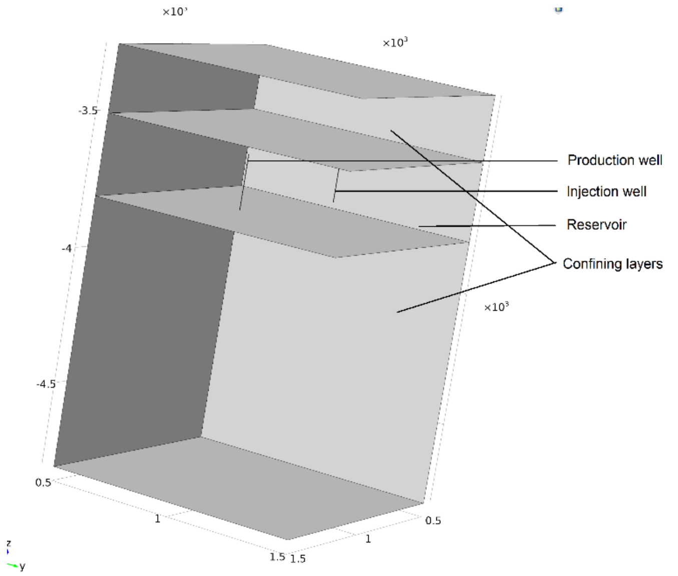

Figure 1 Model geometry

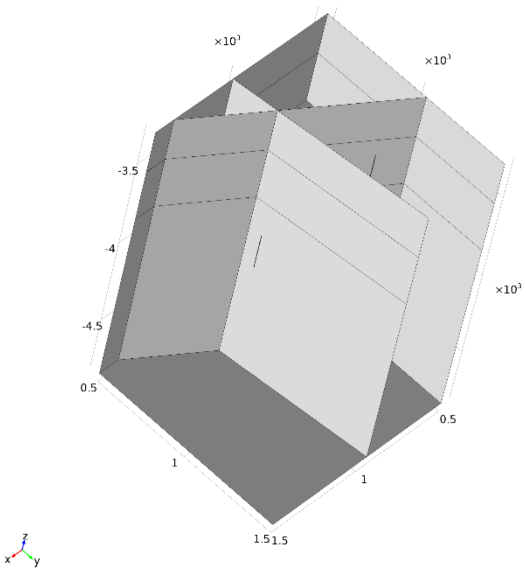

Figure 2 Example of a fault network

3-D fault networks are created, in which a fault is represented by a flat rectangular extending to the boundaries of the model. All the faults are vertical. Azimuth and placing are chosen randomly until the given fault density is reached. The fault network that has been generated as the base case is shown in figure 2.

In this model, two types of rock properties have been used: Reservoir rock and confining layer rock. The confining layers have typical properties of shale layers, so are very impermeable for fluid flow. The reservoir rock has properties typical for tight sandstone. The properties for the base case are listed in table one.

Table 1 Rock properties

Property	Reservoir	Confining layers
Porosity	0.25	0.1
Permeability (m^2)	1e-13	1e-18
Thermal conductivity (W/(m*K))	2.8	2
Density (kg/m^3)	2700	2500
Heat capacity (J/(kg*K))	1098	1100

The faults are partly filled with rock material. Therefore, the fault material is represented by a rock with a very high porosity and density. The properties of the faults are listed in table 2. The properties of the reservoir fluid are listed in table 3. In this research, the density of the reservoir fluid plays a big role, because the temperature differences cause free convection. Therefore an accurate estimation of the temperature dependency of the density is required. Kell (1975) found the following relation between the density of water and temperature, which is used in this model.

$$\rho\left(\frac{kg}{m^3}\right) = (999.83952 + 16.945176t - 7.9870401 * 10^{-3}\, t^2 - 46.170461 * 10^{-6} t^3 + 105.56302 * 10^{-9}\, t^4 - 280.54253 * 10^{-12}\, t^5) /(1 + 16.897850 * 10^{-3} t) \quad (10)$$

In which *t* is the temperature in degrees Celsius.

Table 2 Fault properties

Property	Faults
Porosity	0.8
Permeability (m^2)	1e-9
Thermal conductivity (W/(m*K))	2
Density (kg/m^3)	2700
Heat capacity (J/(kg*K))	1098

Table 3 Reservoir fluid properties

Property	Value
Dynamic viscosity (Pa*s)	3e-4
Ratio of specific heats	1
Heat capacity (J/(kg*K)	4500
Thermal conductivity (W/m*K))	0.68
Compressibility of fluid (1/Pa)	5 e -10

4.2 Boundary Conditions

Boundary conditions are a very important part of the model, since they form the supply of recharge to the main reservoir. The reservoir is confined by two layering beds. The bed on top of the reservoir has a 250 meter thickness. The characteristic time it takes for temperature to propagate through these beds is given by:

$$\tau = \frac{l^2}{k} \quad (11)$$

In which l is the thickness of the confining beds, and k l the thermal diffusivity. For 250 meters thickness the characteristic time will be 1983 years, which is much longer than the lifetime of the reservoir. Therefore, the boundary conditions can be considered insignificant (Poulsen, Balling, & Nielsen, 2015).

The bottom of the reservoir is confined by a much thicker layer, of which the thickness will be changed during the sensitivity analysis. The bottom layer has a larger thickness because the length of the faults under the reservoir is expected to be important for recharge due to gravitational effects. The effect of the upper confining layer on free convection because heated water will flow upwards, and therefore have no effect on the reservoir which is beneath this layer.

The initial temperature of the centre of the reservoir is chosen to be 140 °C, and an injection temperature of 40 °C is used. Due to the faults inside the reservoir and confining layers the effective thermal conductivity of those domains will be higher than typical in the Netherlands. A geothermal gradient of 0.003 °C/m is used, chosen by using a typical faulted reservoir investigated by Baujard et al. (2017). This value is relatively low, because the higher thermal conductivity causes the temperature to be rather constant over the reservoir. A heat flux of 0.065 W/m^2 was applied to the bottom of the lower confining layer, which is a normal value for the Netherlands (de Mooij, 2010).

There are no flow and no heat conditions defined at the side boundaries of the model. These boundary conditions ensure that there is no energy loss or gain in the model except by convection or conduction from the surrounding layers.

4.3 Mesh

The mesh used in the model for the base case is shown in figure 3. At the edges of the faults there is an extra fine mesh defined A higher precision is needed there, because there are big temperature differences around these edges. The total number of tetrahedrons is 322867, and the total number of degrees of freedom is 135978.

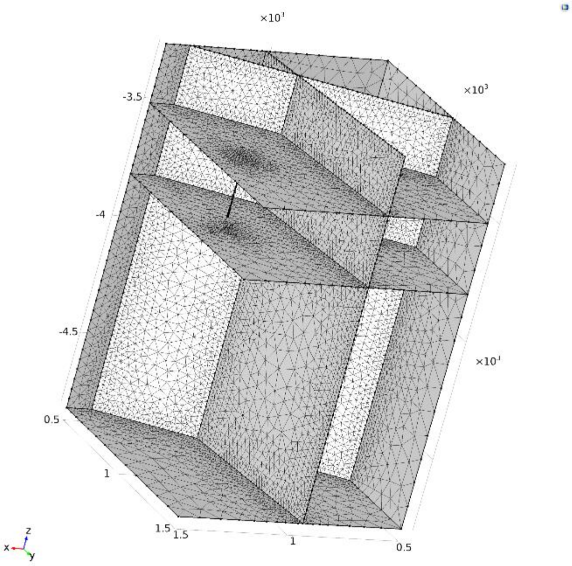

Figure 3 Mesh base case

4.4 Sensitivity Analysis

Uncertainty can cause major challenges in reservoir engineering. This makes an accurate uncertainty analysis very important within this field of research. During this research simulations are created to determine which parameters have most significant impact on the reservoir. In order to perform this sensitivity analysis, the outcome of the model is calculating with varying inputs. The parameters changed during the sensitivity analysis and the range over which they change are listed in table 3. In this table, the fault density is calculated by the area of the faults within the reservoirs, divided by the total volume of the reservoir. The fault height is defined as the total height of the faults from the top of the higher confining layer to the bottom of the lower confining layer. The height of this fault is changed by changing the thickness of the lower confining layer. The range of thermal conductivity of the reservoir rock is chosen by the range of thermal conductivities of different kinds of felsic igneous rocks (Robertson, 1988).

Table 3 Sensitivity analysis parameters

Parameter	Range
Fault aperture	0.2, 0.1, 0.01, 0.001 (m)
Fault permeability	1e-8, 1e-9, 1e-10, 1e-11, 1e-12, 1e-13, 1e-14, 1e-15(m^2)
Thermal conductivity of confining layers	1, 1.8, 2.7, 3.5 (W/(m*K))
Thermal conductivity of reservoir rock	1.8, 2.3, 2.8, 3.2 (W/(m*K))
Fault density	0.0020, 0.0025, 0.003 0.0035 (1/m)
Fault height	650, 1150, 1350, 1550, 1750,1950, 2150 (m)

5 Assumptions

This model is made under in order a few assumptions in order to keep the model simple and reduce the computational time. The assumptions are listed below

1. There is laminar flow in the whole domain of the model.
2. All reservoir fluid/rock properties are constant, except for fluid density.
3. Thermal recharge consists only of conduction from adjacent layers and free convection through the faults by gravity effects.
4. There is no energy loss to adjacent rock formations outside the model.

6 Results and discussion

6.1 Base case

The results for the base case are presented in this section. The uncertainty analysis is carried out on this base case. The temperature distribution after 1, 5, 15 and 30 years is presented in figure 4, 5, 6 and 7. The influence of the faults can be noticed clearly, because cold water moves easily through the faults because of the high permeability. Therefore, the faults are relatively cold compared to its surroundings. The streamlines are represented in those figures by thin white lines. It is visible that free convection increases over years, because there occur more and more streams in the faults due to density differences.

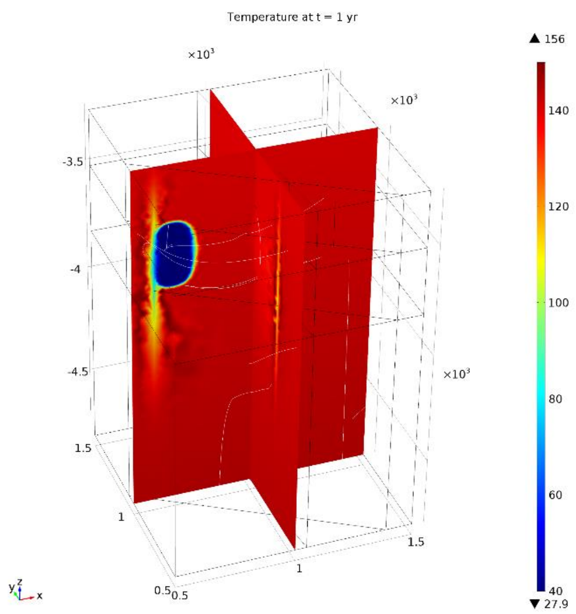

Figure 4 Temperature distribution at t=1

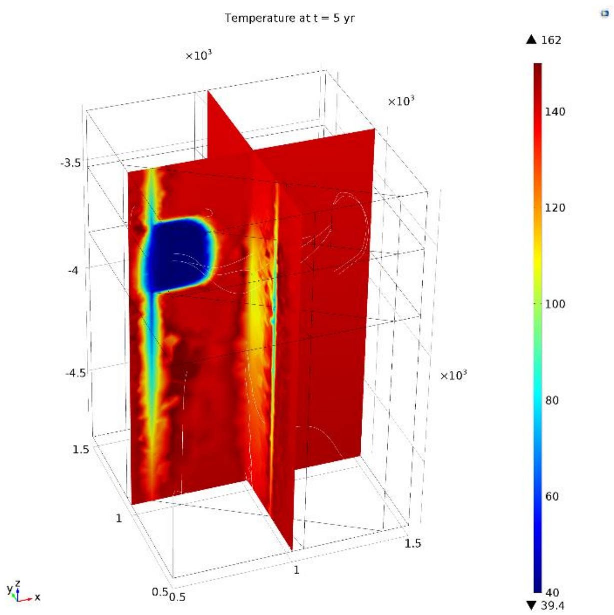

Figure 5 Temperature distribution at t=5

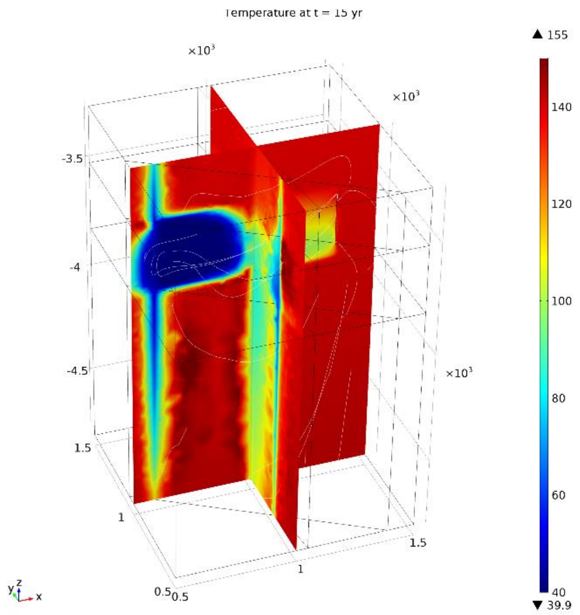

Figure 6 Temperature distribution at t =15

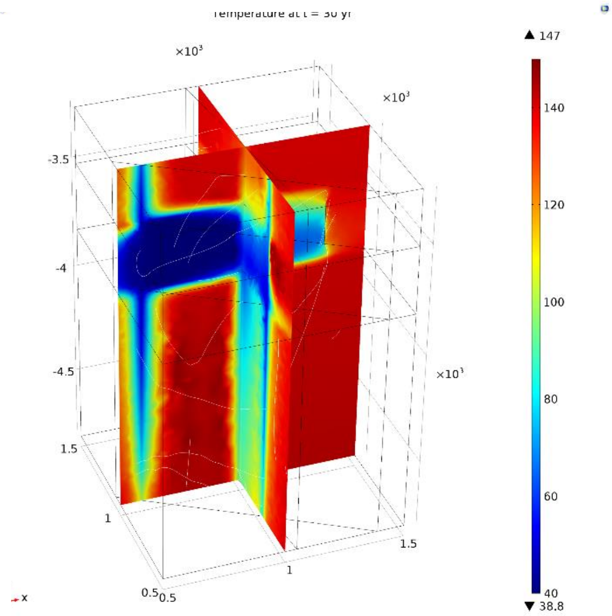

Figure 7 Temperature distribution at t=30

The number above the legends of figure 4, 5, 6, and 7 shows the maximum temperature in the reservoir. There is an overshoot in temperature in some nodes because the maximum temperature exceeds the maximum initial temperature. After 30 years, there are 170 nodes which have an overshoot in temperature. This is relatively small compared to the total number of nodes (0.3%). The cause of this error could for example be because of the big difference between fault and matrix permeability. However, after 5 years the percentage of nodes which overshoot the maximum temperature, which is 2.9%, is much bigger. Therefore, the model can be improved in order to make this error smaller. For example, a finer mesh could be made, especially at the edges of the faults.

The pressure distribution after 0 and 1 year is shown in figure 8 and 9. There is a very slight change in the first year of production, since the minimum and maximum value changed. After 1 year the pressure distribution is stabilized. The pressure at the production well is lower than the injection well, which causes the forced convection. The pressure distribution stays constant during the circulation time.

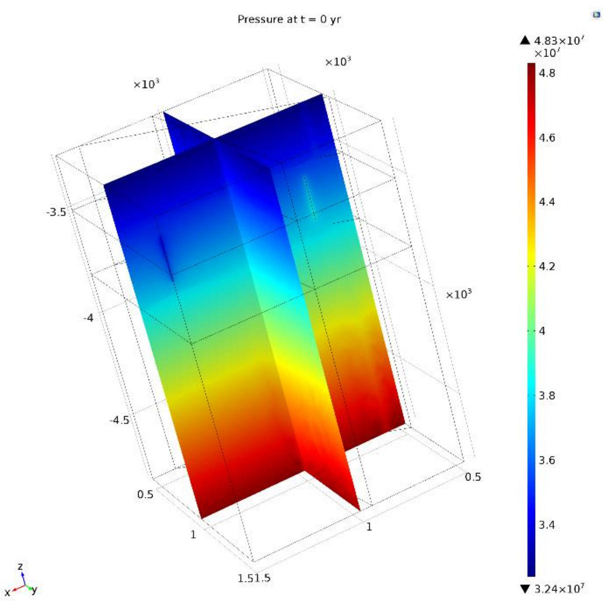

Figure 8 pressure distribution at t=0

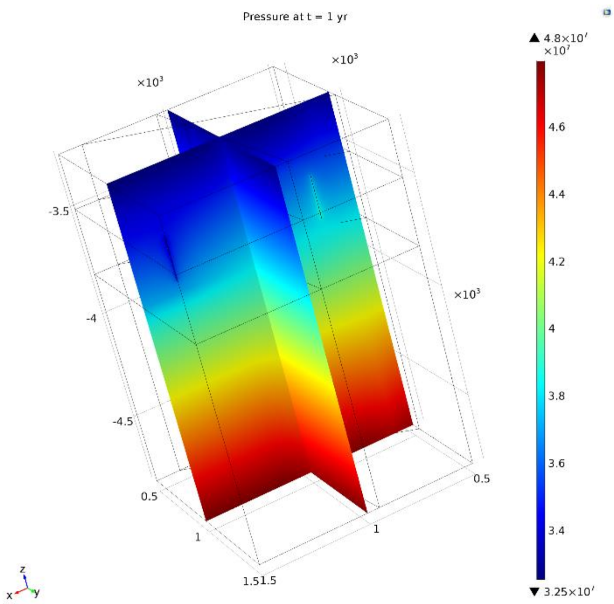

Figure 9 Pressure distribution at t=1

The thermal recharge by free convection is shown in figure 10, and the production temperature is shown in figure 11.

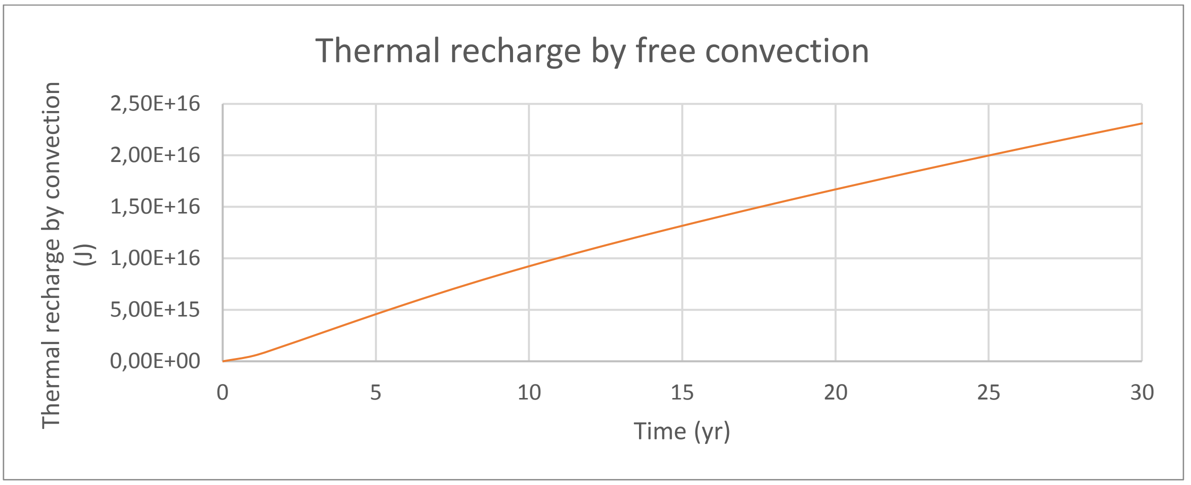

Figure 10 Thermal recharge by free convection base case

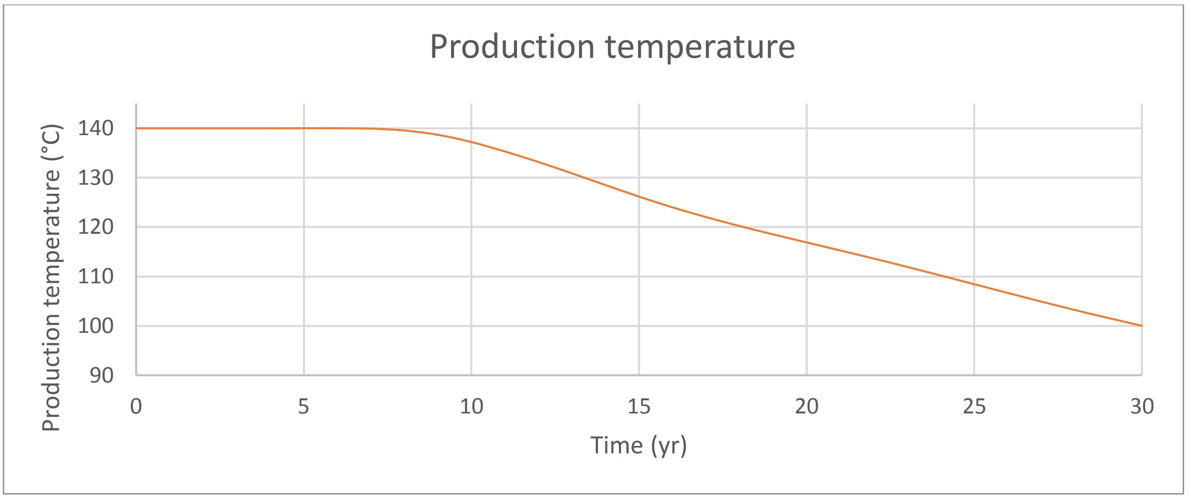

Figure 11 Production temperature base case

In figure 12, the thermal recharge by conduction over the layer boundaries and the thermal recharge by free conduction are shown as a percentage of produced energy. The free convection becomes after 5 years a very big important part of the produced energy, while the conduction over layer boundaries stays very small (<1%).

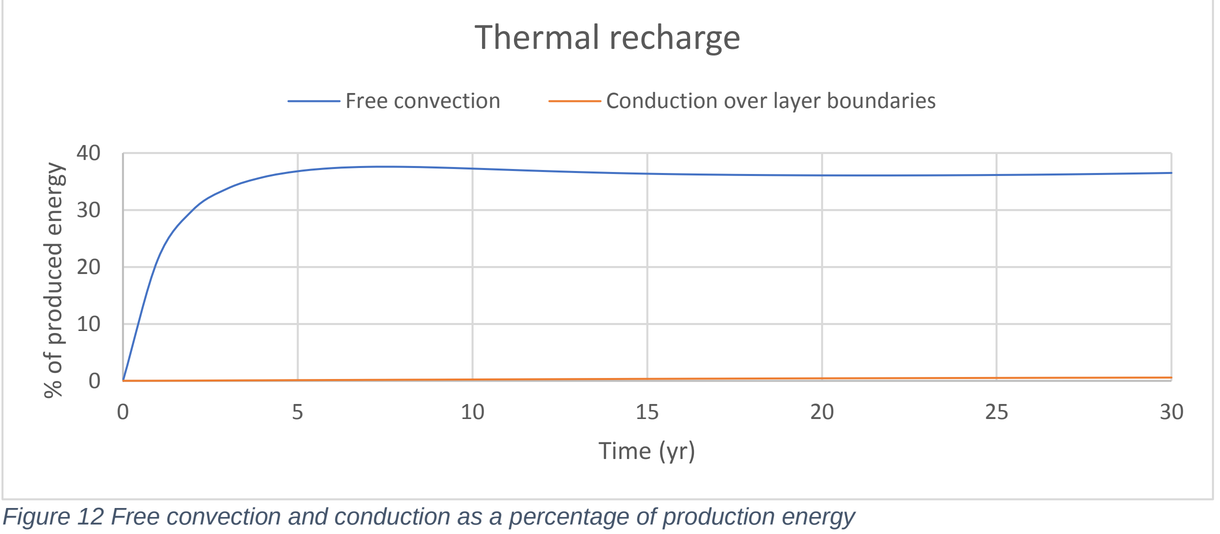

Figure 12 Free convection and conduction as a percentage of production energy

6.2 Fault aperture

As we see from the results in figure 12 and 13, fault aperture has significant impact on thermal recharge and production temperature. Figure 12 shows the thermal recharge by convection simulated by using different fault aperture values varying from 0.2 to 0.001 meter. The results show that a bigger fracture aperture causes a bigger influence of free convection. From this graph, the conclusion can be also be made that the smaller the aperture becomes, the smaller the impact of a change in aperture will become, since the difference in impact between 0.001 and 0.01 meter aperture is smaller than the difference between 0.2 and 0.1.

The results of thermal recharge are consistent with the results of the production temperature. The more free convection, the longer the lifetime of the geothermal systems because of a larger recharge value. However, it is noticeable that during the first 17 years of production this relation seems different. This is mainly because the reservoir will cool down slower when the faults are thinner, because the cold injected water reaches the production well later. After approximately 17 years the impact of free convection becomes big enough to overrule this effect. For example, in the case of the smallest fault aperture, which is 0.001 m, the faults have the least influence. Therefore, the cold injected water in will flow relatively slowly to the production well, because there is less space to flow through the faults. This causes the production temperature to stay longer at 140 °C. However, because there is less flow in the faults, there will be less free convection and the reservoir will be less recharged. Consequently, the reservoir will cool down relatively fast and the production temperature will also decrease relatively fast. After a certain time, the production temperature will be lowest in the case of this fault aperture and therefore in the end have the shortest reservoir lifetime.

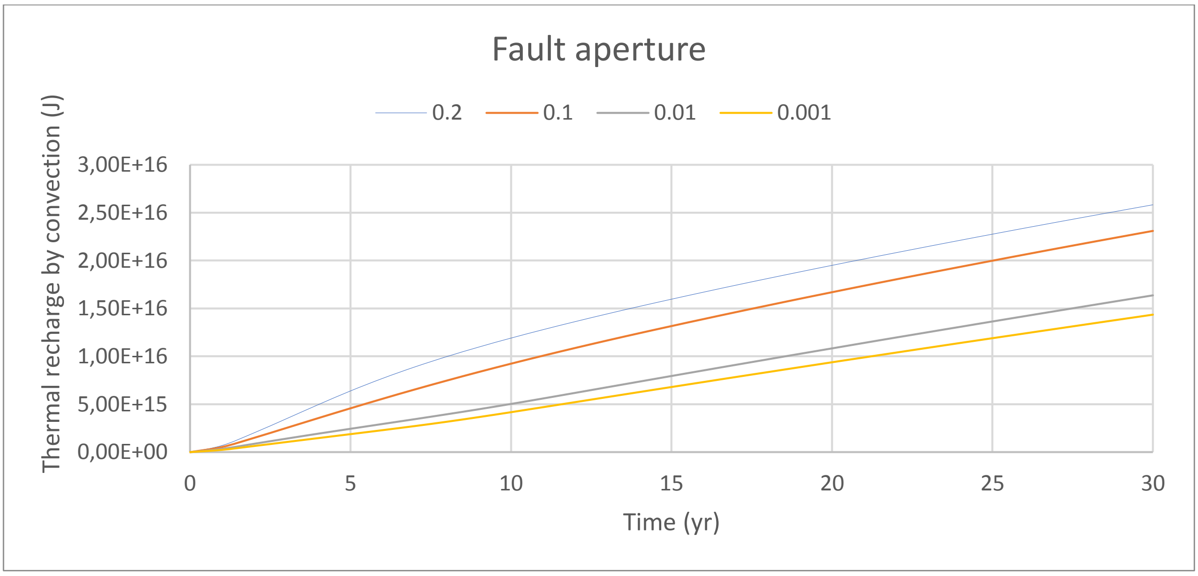

Figure 12 Thermal recharge by convection with varying fault aperture

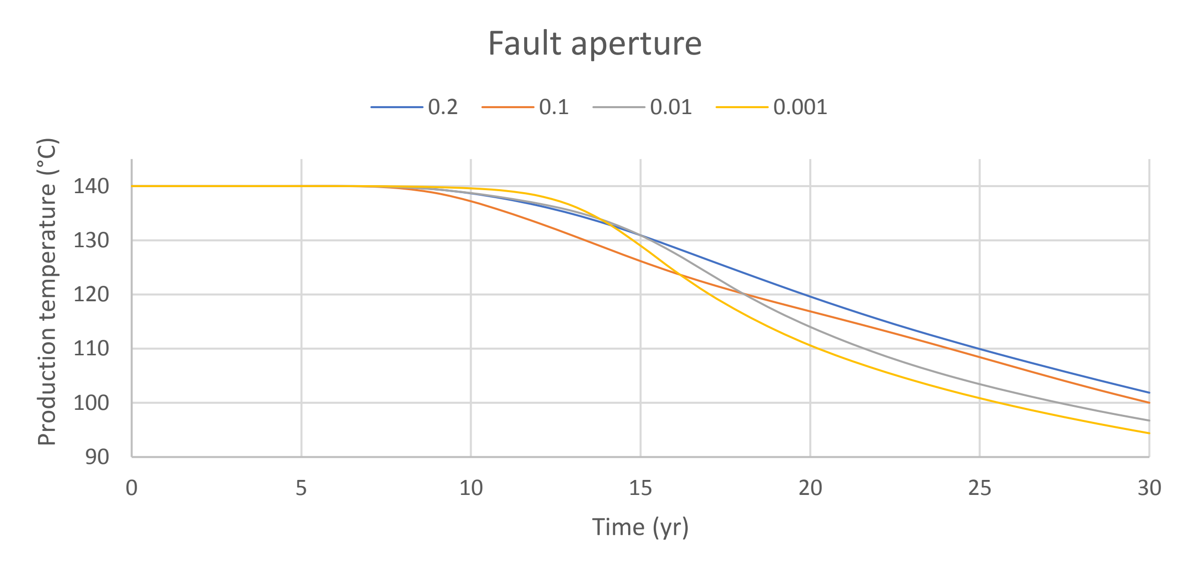

Figure 13 Production temperature with varying fault aperture

6.3 Fault height

The results of the sensitivity analysis using fault height show very clear results. Figure 14 shows that a bigger fault height causes more convection. This is as expected, since a longer fault can supply more heat to the reservoir, because there is more surface area of the fault connected to the warmer confining layers. If this surface area is beneath the reservoir, density differences in the fluid will bring the warm water to the reservoir.

Figure 15 shows that the amount of recharge has significant impact on the production temperature. Longer faults cause more convection, and therefore the production temperature is higher. Because of that, the lifetime of the reservoir will be higher.

There is a very small difference in results between a fault height of 1950 meters and 2150 meters, therefore it is expected that above a fault height of 2150 the fault height will not make a significant difference in result anymore. The smallest fault height investigated is 650 meters. In this case the lower confining layer is only 100 meters thick. The amount of recharge by free convection is much lower than with bigger fault heights, but still not close to zero. This means the minimum fault height to have significant impact of free convection is below 650 meters.

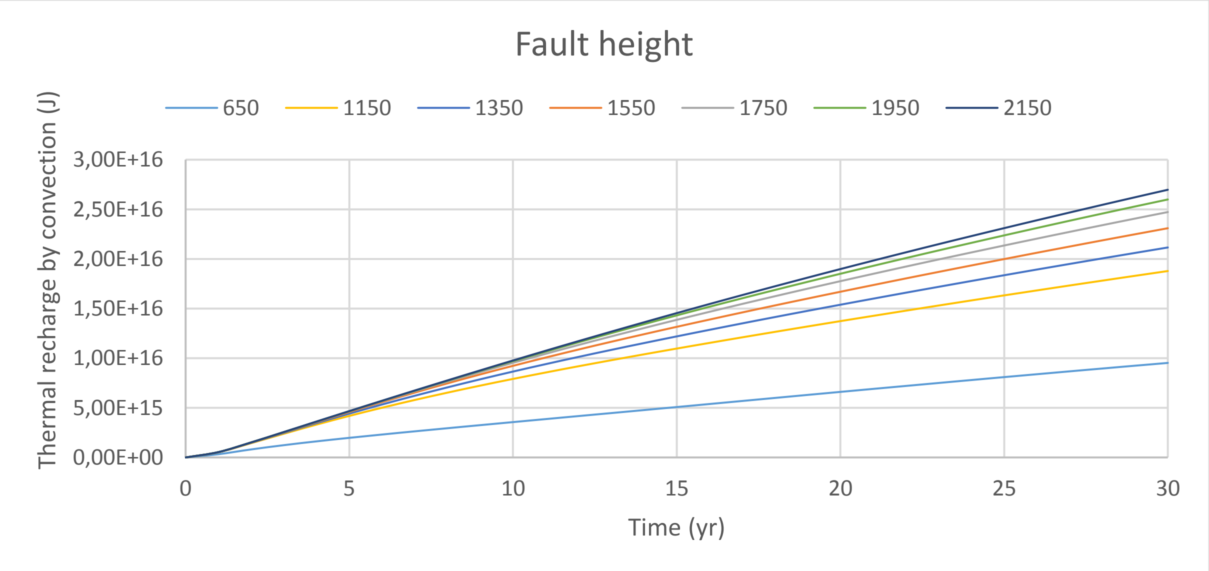

Figure 14 Thermal recharge by convection with varying fault height

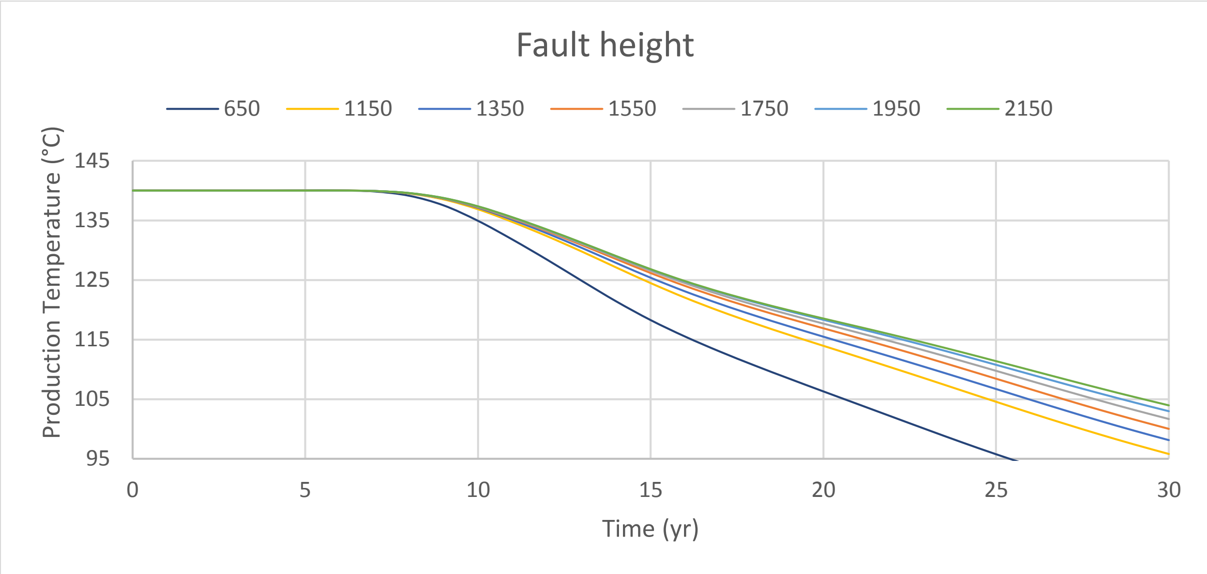

Figure 15 Production temperature with varying fault height

6.4 Fault density

As shown in figure 16 and 17, fault density does certainly have influence on the reservoir temperature during production. However, the relation between fault density and thermal recharge is not very clear. A higher fault density should cause more thermal recharge, because of the free convection which is mainly present in faults, however this is not the case. After thirty years the fault density of 0.0035, which is the highest value assessed shows indeed the most thermal recharge and the density of 0.002 the least. Yet, the density values in between seem to be switched.

This has possibly to do with the connectivity index and the fractal dimensions which are listed in table 4. The connectivity index is a measure which quantifies the probability of a connection between faults in a fault network (Fadakar Alghalandis, Xu, & Downd, 2013), which can be very important for production temperature. A high connectivity index can cause a higher permeability of the reservoir, and therefore the cold injected water can more easily reach the production well, which decreases the production life time. Even though, this is not visible in the results, because the fault-set with a density of 0.002 has a low connectivity index, but keeps the longest the initial production temperature. The fractal dimension is a measure to characterize self-similarity in a network (Sarkar & Chaudhuri, 1994). A high fractal dimension would mean that there is a very regular fault distribution over the reservoir, which could be beneficial for the recharge. However, this result is also not clearly visible in figure 16.

Another factor which is not quantified in this research can have influence on the thermal recharge. This factor is the placing of the faults relative to the injection and production well. For example, a fault network which connects the injection well directly to the production well, would influence the results because the cold injected water can directly flow to the production well. If the faults are further away from the injection well this effect will be reduced.

Therefore, it is necessary to do more research on the influence on the above mentioned factors on thermal recharge. The fault networks generated have too many factors influencing the reservoir temperature to make a well-considered conclusion on the influence of fault density.

Table 4 Properties of fault networks used in sensitivity analysis

Fault density	Connectivity index	Fractal dimension
0.002	0.5	1.820
0.0025	0.67	1.969
0.003	0.75	2.083
0.0035	0.5	2.083

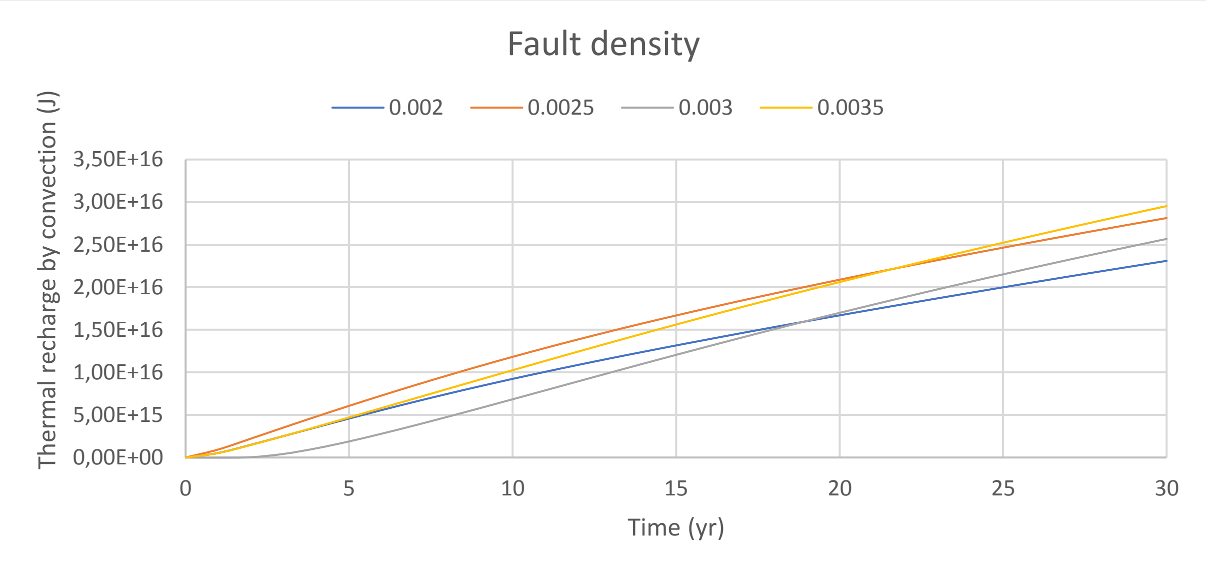

Figure 16 Thermal recharge by convection with varying fault density

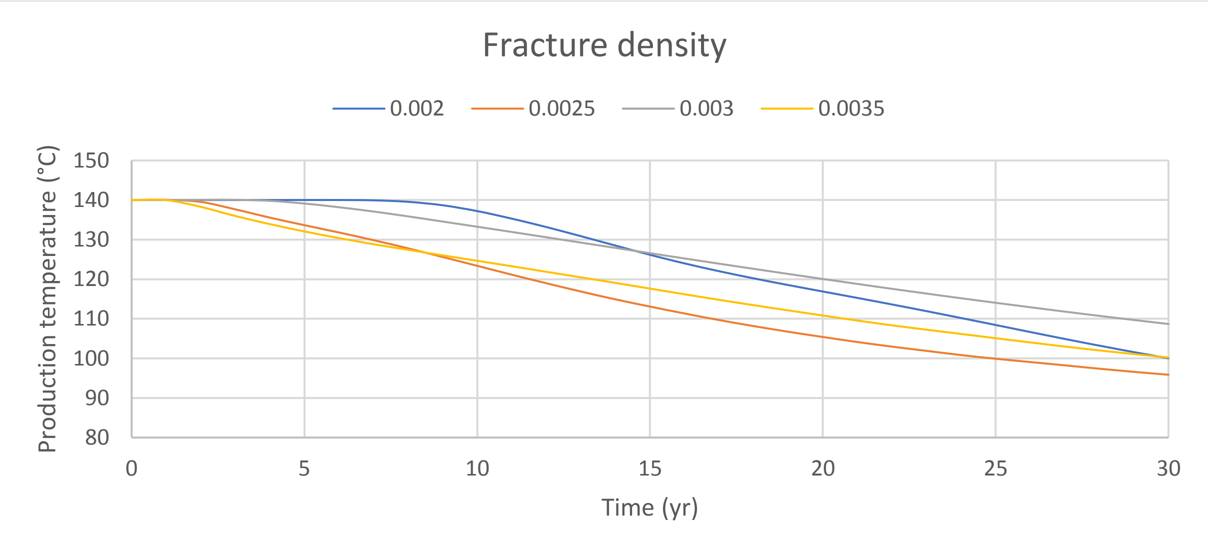

Figure 17 Production temperature with varying fault density

6.5 Fault permeability

The results of the sensitivity analysis on fault permeability are shown in figure 18 and 19. In the permeability range of 1 E-8 until 1E -11 m^2 a clear relation between fault permeability and thermal recharge by free convection. A higher permeability allows the fluid to flow more easily, so that the heated fluid in the lower confining layer can easily flow to the reservoir to recharge it. This effect, in the above-mentioned range of permeability values, is also visible in the production temperature. However, it takes some time for the high-permeability values to have a positive impact on the production temperature. This is because of the same effect as discussed in the section about fault aperture. A lower fault permeability will at first cause the production temperature to stay at 140 °C for longer, because a lower fault permeability causes the cold injected water to flow slower to the production well. On the other hand, there will occur less free convection. Therefore, after a certain time the reservoir will cool down relatively fast, and the production temperature will become lower than cases with a higher fault permeability.

The sensitivity of the model is also tested with fault permeability values lower than 1 E-11 m^2, in order to see under which permeability value there would be no significant free convection anymore. Surprisingly enough, all values below 1 E-11 m^2 give the same results, and show that there is in each scenario still thermal recharge present. Even when looking at a fault permeability which is lower than the permeability of the reservoir rock there is still an effect of free convection present. This result does not seem reliable, and therefore more research is needed on this topic.

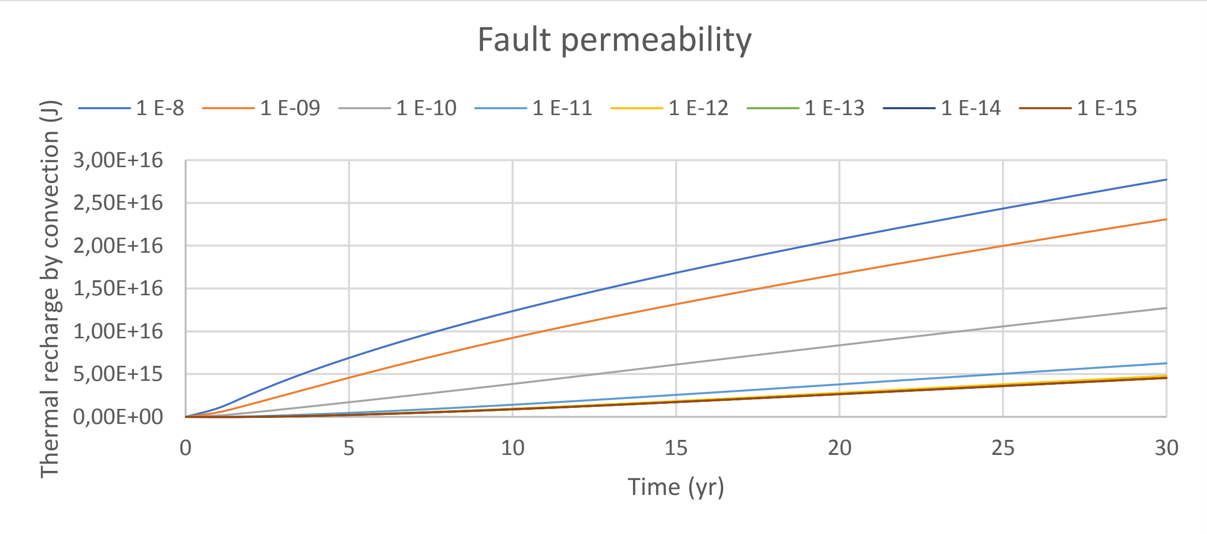

Figure 18 Thermal recharge with varying fault permeability

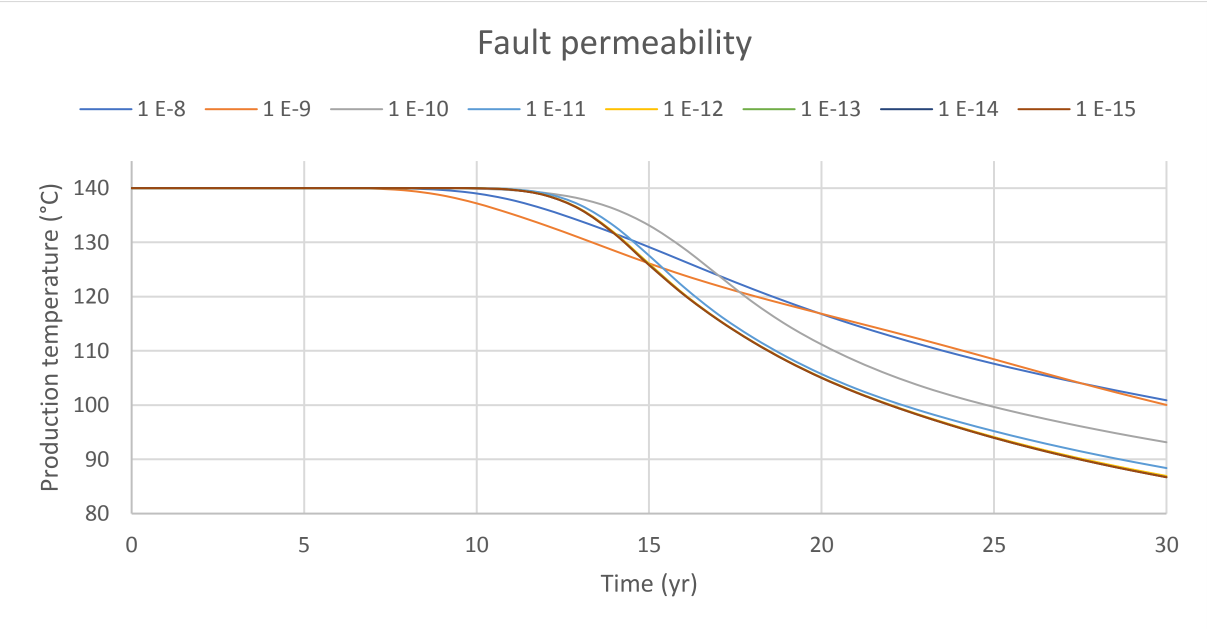

Figure 19 Production temperature with varying fault permeability

6.6 Thermal conductivity of the reservoir

The results of the sensitivity analysis about thermal conductivity of the reservoir rock are shown in figure 20 and 21. The lines all exactly overlap each other, and therefore this factor has no significant effect on the thermal recharge by free convection or on the production temperature. These results are not as expected because in theory a higher thermal conductivity would allow the reservoir rock to be heated more easily by the water which is warmed up by the lower confining layer and because of that transported by free convection. Therefore, more research is needed to asses if these results are reliable and if so, why the thermal conductivity of the reservoir rock has no effect on the free convection.

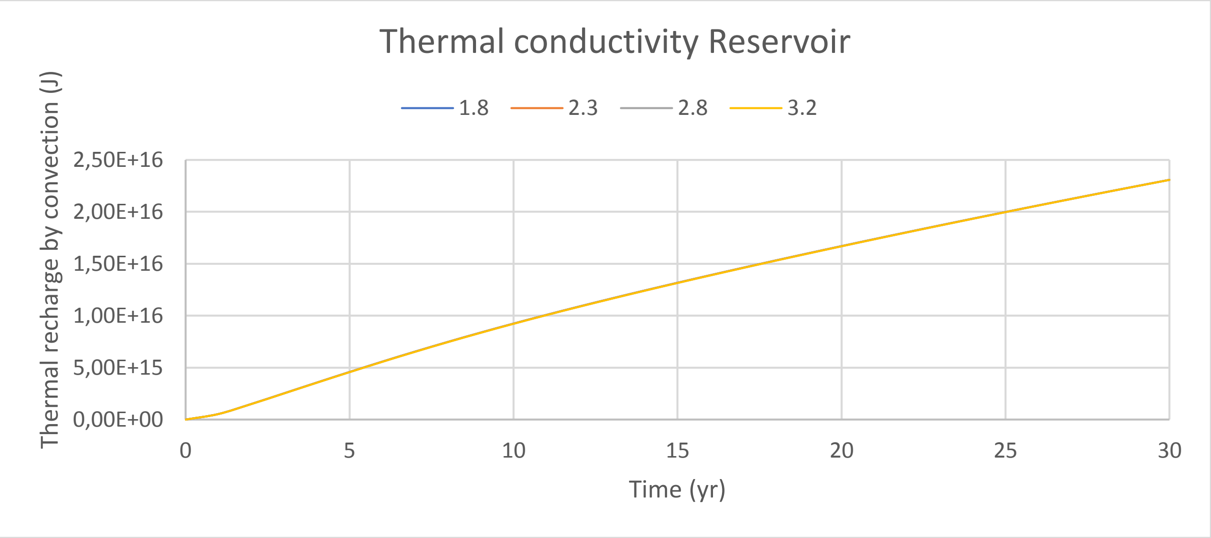

Figure 20 Thermal recharge with varying thermal conductivity of reservoir rock

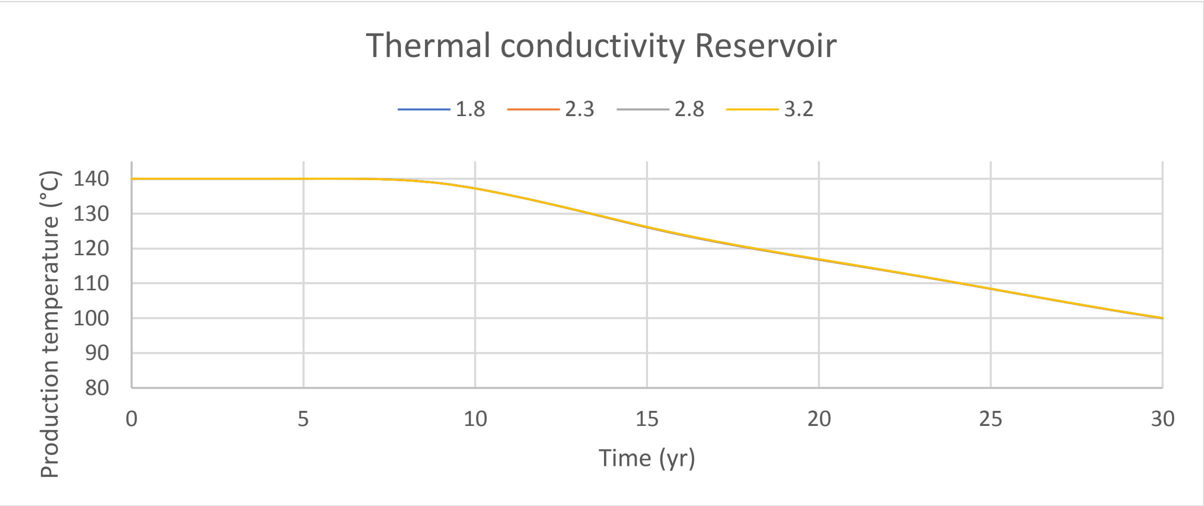

Figure 11 Production temperature with varying thermal conductivity of reservoir rock

6.7 Thermal conductivity of confining layers

Unlike the results of the previous section, the thermal conductivity of the confining layers does have significant effect on the thermal recharge by free convection and the production temperature, shown in figure 22 and 23. The clear relation can be seen that a higher thermal conductivity in the confining layer causes more thermal recharge by free convection and therefore, the production temperature stays higher. Accordingly, a higher thermal conductivity of the confining layers increases the lifetime of the reservoir.

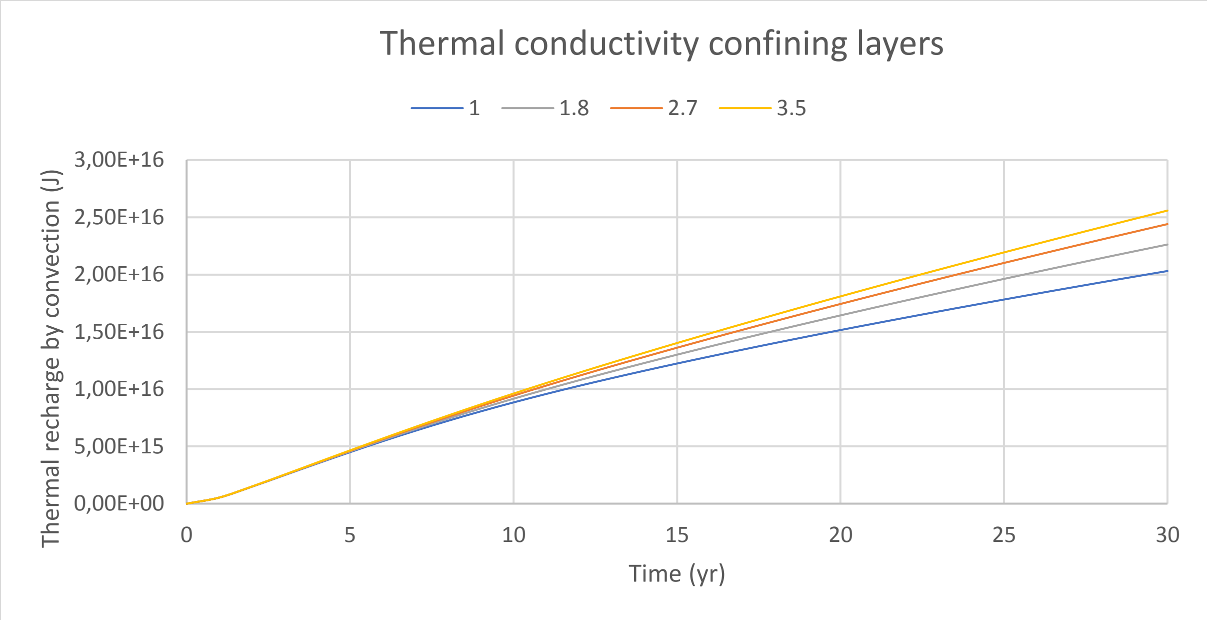

Figure 22 Thermal recharge by convection with varying thermal conductivity of confining layers

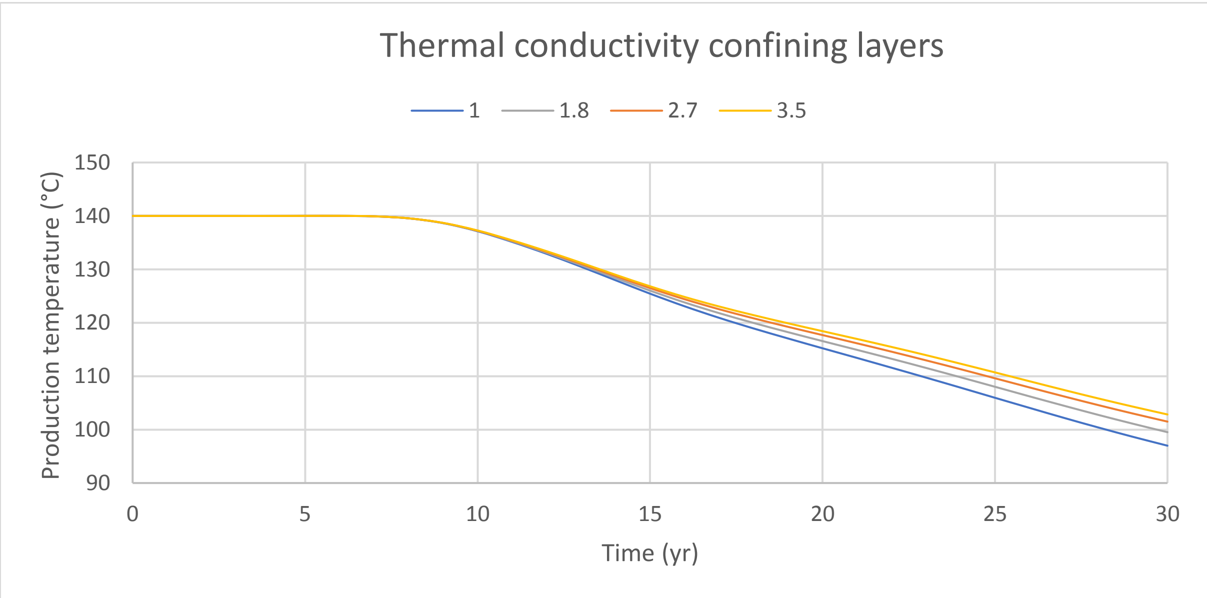

Figure 23 Production temperature with varying thermal conductivity of confining layers

Conclusion

In this study, a coupled numerical model is built in Comsol Multiphysics in order to calculate the thermal recharge by free convection during the first 30 years of energy production. A sensitivity analyses is carried out to find which parameters have most significant impact. The sensitivity analysis is focused on fault properties.

Based on the results of this study the following conclusions can be made. Free convection has significant impact on a reservoir with large faults. The base case of the sensitivity analysis shows that free convection can reach over 35% of the produced energy. Therefore, it is important to consider the free convection in estimating the recoverable energy from the reservoir.

Fault aperture, Fault height, Fault permeability and thermal conductivity of the confining layers have a positive influence on the thermal recharge by free convection of a faulted geothermal system. It is also found that fault aperture, fault length and thermal conductivity of the confining layers have a direct influence on the production temperature of the geothermal system. Fault permeability does increase the production lifetime, but in the beginning of the production time it decreases the production temperature. After a certain time, the increased effects of free convection become big enough to have a relatively higher production temperature.

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