Breakthrough time of a geothermal reservoir

Estimating the impact of well spacing, reservoir and operational inputs on the breakthrough time of a geothermal doublet

By

S. van Rijn

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Supervisor:	Prof. Dr. D.F. Bruhn, TU Delft
Co-supervisor:	Mr. A. Daniilidis, TU Delft
Thesis coordinator:	Ms. Y. de las Heras

TUDelft

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Nomenclature

Symbol	Description	Unit
A	Area	m^2
u	Darcy velocity	ms^{-1}
ρ	Density	kgm^{-3}
h	Depth	m
μ	Dynamic viscosity	Pa·s
Q	Flow rate	m^3h^{-1}
g	Gravitational acceleration	ms^{-2}
C	Specific heat capacity	$Jkg^{-1}K^{-1}$
q	Heat rate	Wm^{-2}
L	Length	m
M	Mass flow rate	kgs^{-1}
J	Mass flux	$kgm^{-2}s^{-1}$
T	Temperature	K or °C
p	Pressure	Pa
k	Permeability	m^2
d	Pore diameter	m
φ	Porosity	-
r	Radius	m
Re	Reynolds number	-
λ	Thermal conductivity	$Wm^{-1}K^{-1}$
H	Thickness of aquifer	m
t	Time	years or s
V	Volume	m^3

Subscripts

Symbol	Description
b	Bulk
m	Mass
w	Water
0	Initial state
inj	Injection
hf	Heat flux
hs	Heat source

Abstract

This research identifies and provides a relative ranking of the parameters that control the thermal breakthrough time of a geothermal doublet. The ranking is based on simulations modelled by a three-dimensional model build in COMSOL Multiphysics with a simulation duration of 50 years. The model is a nonisothermal, isotropic, cuboid consisting of a sandstone aquifer surrounded by identical impermeable layers. The ranking is derived based on a solution space covering a minimum, maximum and mean value for each of the simulation parameters. The investigated simulation parameters are the density, porosity, permeability, thermal conductivity and specific heat capacity of both the surrounding rock formations and the aquifer, the depth and thickness of the aquifer, the flow rate, injection temperature and the well spacing. The mean values of the solution space form the base model, from which the parameters will divert separately to monitor the model's behaviour on the varying parameters.

In this research, the breakthrough time is defined as the time at which the production temperature is decreased by 1% to 99% of its initial value. The ranking is based on comparing the proportional change of each parameter from the base model to the change in breakthrough time. The results show that the thickness, flow rate and the well spacing are the most crucial parameters influencing the thermal breakthrough time of a reservoir. Overall, the flow rate has the greatest impact, with a decrease of 16.7 years between a flow rate of 150 m^3/hour and 250 m^3/hour.

In addition, the surrounding rock parameters have a notably smaller impact on the thermal breakthrough time compared to the reservoir rock and process parameters. The surrounding rock parameter with the relatively largest impact on the breakthrough time is the specific heat capacity, which is only a change of 0.2 years between a specific heat capacity of 1150 and 1250 $Jkg^{-1}K^{-1}$.

Acknowledgements

1 Introduction

In 2016, only 6% of the total energy consumption in the Netherlands is produced by renewable energy (Eurostat, 2018). As shown in figure 1, this is the lowest shares in renewable energy in Europe after Luxembourg (Eurostat, 2018). In that same year, the Netherlands agreed to increase its share in renewable energy to 14% by 2020 (Ministerie van Economische Zaken, 2016). To achieve this target, the Netherlands is subsidising renewable energy projects and is focussing more on supporting new technical developments. One of the technological developments that seems a suitable and affordable solution to reduce the dependence of the Netherlands on fossil fuels is geothermal energy.
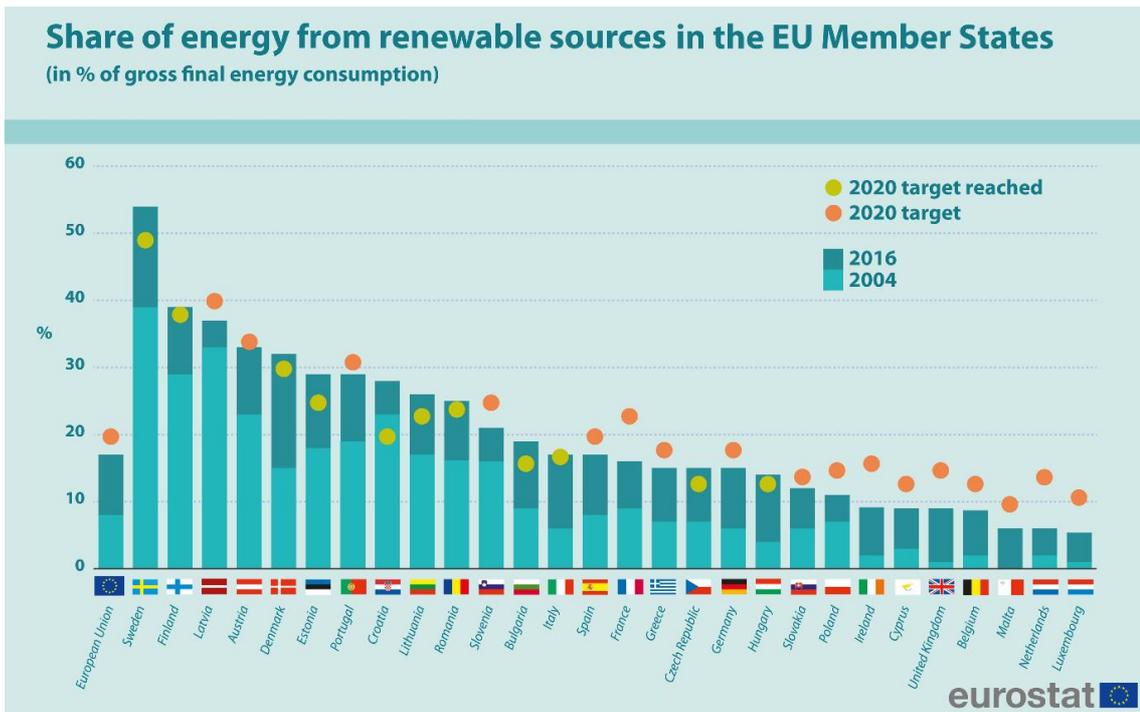
Figure 1: Illustration showing the share of renewable energy sources in the EU Member States (Eurostat, 2018)

1.1 Scope

Geothermal energy is the thermal energy present beneath the Earth's surface. Geothermal energy originates from the heat generated by the decay of radioactive isotopes, mainly ^{40}K, ^{232}Th, ^{235}U and ^{238}U, and the heat generated from the original formation of the planet (Barbier, 2002).

The main distinction between geothermal projects is whether the heated water is directly used for heating households and greenhouses or whether the heated water generates electricity. To generate electricity, a temperature above 150 °C is often necessary (Lund, 2007). Since the average thermal gradient in the Netherlands is 31.3 °C/km (Bonté et al., 2012), this would require an aquifer at a depth of around 4000 meters. Because of this, research in geothermal projects in the Netherlands is mainly focussed on relatively shallow low temperature geothermal reservoirs.

The heat from water with a lower temperature is mostly extracted by a binary cycle. In binary plants, the hot water is passed by a secondary fluid with a much lower boiling point. This causes the secondary fluid to turn

to vapour, which then drives a turbine. The low-enthalpy water is mostly produced by a doublet configuration. A doublet configuration is a system with two wells; the first well is used to produce the hot water and the second well to reinject the cold water back into the same aquifer. Reinjection of the water is essential to maintain the pressure in the reservoir.

Figure 2: Geothermal doublet configuration (Agemar, 2014)

1.2   Problem statement

There are many advantages of geothermal energy. It can be extracted without burning fossil fuels, the binary plant mentioned above releases essentially no emissions (Lund, 2007) and the energy is always available. Besides, there is no noise or landscape pollution (van Heekeren, 2011) in contrary with for example wind turbines.

However, already in the early planning phases, investing in a geothermal project has a high level of risks. For example, the production temperature and flow rate (the output power) and the life time that may be expected are uncertainties with a large impact on the benefit of the project. The Netherlands tries to compensate for this uncertainty by subsidising geothermal development for a maximum subsidy duration of 15 years (Actieplan Aardwarmte, 2011). However, this is relatively short considering that for a geothermal doublet configuration with a well spacing of 1 to 2 kilometres, the average production life time could be 30 to 50 years.

The uncertainty in the planning phase not only results from site specific geological uncertainties, which could be solved by more detailed measurements of the subsurface, it is also the result from a lack of understanding of how the aquifer parameters, like permeability, porosity and thickness, will influence the geothermal output. Increasing the knowledge on the impact that certain parameters have on the geothermal output and thus the thermal breakthrough time, would benefit the investors and the geothermal science in general.

1.3   Aim & Objectives

Considering the issues discussed earlier, this research tackles the primary problem, which is the thermal breakthrough time. The thermal breakthrough time is the time that it takes for the cold water to reach the production well. After thermal breakthrough, the production temperature starts to decline until production is no longer profitable. The thermal breakthrough time is dependent on a wide variety of parameters. This research aims to identify and provide a relative ranking of the parameters that control the thermal breakthrough time of a geothermal doublet.

Arguments justifying this ranking are formed through the following objectives:
1) Determine the relevant reservoir and process parameters that have a possible influence on the thermal breakthrough time.
2) Compute a solution space covering ranges of the parameters discussed
3) Identify the relative ranking of the considered parameters that control thermal breakthrough.

To reach these objectives, a geothermal doublet configuration is simulated in a coupled hydraulic-thermal three-dimensional model, using COMSOL Multiphysics 5.3a.

1.4   Outline

First, the differential equations describing the fluid flow and heat transfer mechanisms will be discussed in chapter 2. This chapter also discusses the governing equations used to calculate the breakthrough time on

which the sensitivity analysis is based. In chapter 3 the various reservoir, process and surrounding rock parameters are discussed and determined. For each parameter, a minimum, mean and maximum value are determined based on literature search and assumptions. These parameter ranges are implemented in the model described in chapter 4. The results and findings are visualised and discussed in chapter 5. Chapter 6 concludes these findings, while chapter 7 gives recommendations for further research.

2 Analytical Background

The performance of the geothermal doublet can be completely described by differential equations that depict the laminar flow behaviour and the heat transfer in porous media. In subchapter 2.1 and 2.2, these equations are described. After running the model based on these differential equations, the breakthrough time and the relative ranking of parameters is determined. The definition of the breakthrough time and temperature is explained in subchapter 2.3.

2.1 Fluid Dynamics

There are two main fluid movement mechanisms to analyse this problem. The first fluid mechanism is the forced flow caused by the (re)injection of water at the injection well and the pumping at the production well. This effect is also considered by combining Darcy's law (equation 1) with the continuity equation forming equation 2 and 3. The second fluid mechanism is the natural bulk fluid movement caused by the change in temperature by the (re)injection of cold water and the heat exchange with the surrounding formations. This change in temperature generates a change in density and causes the water to move by the Buoyancy effect. This free convection is considered in the generalised form of Darcy's Law (equation 1) by the gravitational constant and the density factor. In the following subparagraphs, these two equations are described in more detail.

2.1.1 Darcy's Law

Darcy's law describes the one-dimensional flow of a fluid through an isotropic medium. The generalized form applicable for a three-dimensional anisotropic media is described below (De Marsily, 1986):

$$\vec{u} = -\frac{\vec{k}}{\mu}(\nabla p - \rho \vec{g}) \tag{1}$$

Where $\vec{u}$ [m/s] is Darcy's velocity, $\vec{k}$ [m^2] is the permeability of the porous medium, p [Pa] is the pressure, μ [Pa·s] the dynamic viscosity of the fluid, ρ [kg/m^3] is the density and $\vec{g}$ [m/s^2] is the gravitational acceleration.

2.1.2 Continuity Equation

The continuity equation describes the rate at which mass leaves and enters the system, plus the accumulation of mass within the system. Combining the continuity equation with Darcy's Law gives the following formula (Pedlosky, 1987):

$$\frac{\partial}{\partial t}(\varphi \rho) + \nabla \cdot (\rho \vec{u}) = Q \tag{2}$$

Where ρ [kg/m^3] is the density of the fluid, t [s] is the time, φ [-] is the porosity fraction, $\vec{u}$ [m/s] is the Darcy velocity and Q [m^3/h] is the flow rate. The first term on the left-hand side of the equation vanishes since the porosity remains constant. This results in:

$$\nabla \cdot (\rho \vec{u}) = Q \tag{3}$$

The fluid flow caused by the wells is specified as a mass flow rate. The mass flow rate for the injection and production well are oppositely equal and defined by:

$$M = Q \cdot \rho_w \tag{4}$$

Where M [kg/s] is the mass flow rate, Q [m^3/h] is the pumping rate and ρ_w [kg/m^3] is the density of water.

2.1.3 Reynolds number

It has to be noted that Darcy's Law only describes laminar flow. Reynolds number is used to predict the flow patterns in different situations. The Reynolds number [-] for fluid flow through a bed can be defined as (Sommerfeld, 1908):

$$Re = \frac{\rho d u}{\mu \varphi} \tag{5}$$

Where Re is the Reynolds number [-], ρ [kg/m³] is the density of the fluid, u [m/s] is Darcy's velocity, d [m] is the average pore diameter, μ [kg/m·s] the dynamic viscosity of the fluid and φ [-] is the porosity fraction.

The flow is turbulent if $Re > 2.0 \cdot 10^3$ (Rhodes, 1989). This will most likely occur close to the wellbore due to the relatively high flow rates combined with the small well diameters. However, turbulent flow is unrealistic at a further distance from the well, which is the part that is of importance for this study. Because of this, Darcy's Law is applicable for the aquifer and surrounding layers in this (simplified) model.

2.2 Heat transfer in porous media

The heat in the subsurface for a rigid medium fully saturated with water is described by the heat transport equation. This equation considers the conduction by the porous domain and the convection of the fluid.

$$(\rho C)_{eff} \frac{\delta T}{\delta t} + \rho C \vec{u} \cdot \nabla T + \nabla \cdot q_{hf} = q_{hs} \tag{6}$$

$$q_{hf} = -\lambda \nabla T \tag{7}$$

Where t [s] is time, T [K] is the temperature, ρ [kg/m³] is the mass density, C [J/K] is the specific heat capacity, λ [W/(mK)] is the thermal conductivity, $\vec{u}$ [m/s] is the Darcy velocity vector calculated by equation 1 and 2, q_{hf} [W/m²] is the heat flux by conduction and q_{hs} [W/m³] is the heat source.

Since the injected water is specified as a mass flow, the heat source at the injection well is defined by the following formula:

$$q_{hs} = C_w \frac{M}{L_{well}} \left(T_{inj} - T \right) \tag{8}$$

Where C_w [J/(kg·K)] is the water heat capacity, L_{well} the well length, T_{inj} [K] is the injection temperature, M [kg/s] is the mass flow rate, T [K] the current temperature.

2.3 Breakthrough time

The thermal breakthrough time is defined as the time when the first sign of temperature decrease is observed at the production well. For this research, it is determined specifically at the time at which the temperature is decreased by 1% to 99% of its initial value, as shown in equation 9.

$$T_{bt} = 0.99 \cdot T_0 \tag{9}$$

Where T_{bt} [K] is the breakthrough temperature and T_0 is the initial temperature.

3 Definition of the parameters

In this chapter, the relevant reservoir and process parameters that have a possible influence on the thermal breakthrough time will be determined and discussed. Based on literature search, a minimum, mean and maximum value are established for each parameter. The mean values of the parameters form the base model. For each experiment, a parameter will divert from the base model by changing their value to their minimum and maximum. In other words, in each experiment only one parameter is different compared to the base model. To determine the parameter(s) that have the most impact on the breakthrough time, the effect of a proportional change of a single parameter on the breakthrough time will be analysed. At the end of the chapter, the parameters and their range will be summarised in an overall table.

3.1 Reservoir properties

3.1.1 Initial pressure and temperature

The average thermal gradient in the Netherlands is 31.3 °C/km (Bonté et al., 2012). In the Netherlands, the depth of the reservoirs of current geothermal explorations range from 1,600 meters to 3,000 meters ("Geothermie in Nederland," 2018). The mean is taken at 2,300 meters. With an average surface temperature of 10 °C, this results in an initial temperature range from 60 °C to 104 °C. Besides, the saturated initial pore pressure [Pa] also increases with depth, by the following formula:

$$p = \rho g h \tag{10}$$

Where ρ [kg/m^3] is the density of the fluid, g [m/s^2] is the gravitational acceleration and h [m] is the depth. This gives a range in initial pore pressure from 15.7 MPa to 29.43 MPa.

3.1.2 Thickness reservoir

The Netherlands has multiple aquifers that are suited for geothermal extraction with a wide variety of thicknesses. For example, based on log descriptions made by the NAM, the thickness of the Delft Sandstone Member within the Moerkappele field varies from 22 to 128 meters (Wiggers, 2009). While for example the Vlieland Sandstone Formation, another potential geothermal aquifer in the Netherlands, has a thickness ranging from less than a meter to 190 meters (Van Pelt, 2011). Based on this wide variety in thicknesses, the minimum thickness of the aquifer is taken at 20 meters, with a maximum of 180 meters and an average of 100 meters.

3.1.3 Thickness over- and underlying rock

The thickness of the cap and base rock must be large enough to assure that there is no thermal interaction between the outer boundaries and the model and thus that they do not interfere with the model results. To assure this, the model is run a few times with extreme parameter values (highest flow rate, smallest well spacing etc.). By looking at the results of these runs, it could be determined that the thicknesses of the cap and base rock should be at least 5 times the thickness of the aquifer to prevent interaction. The thickness of the aquifer varies from 20 up to 180 meters, which results in an over- and underlying rock thickness ranging from 100 up to 900 meters, with a mean of 500 meters.

3.2 Rock Properties

Sandstone and limestone are two sedimentary rocks which are used as a reservoir rock. In the Netherlands, sandstone as a reservoir rock is more common, for example the Delft Sandstone, Rotliegend Sandstone and the Vlieland formation. Because of this, the reservoir rock in this research is taken as a sandstone formation, which is surrounded by impermeable layers. The over- and underlying rock have equal properties and thicknesses. The properties of the impermeable layers are based on general values for shale and claystone

(Schön, 2015). For the sandstone, the porosity, permeability, density, thermal conductivity and specific heat capacity will be discussed in the following sections.

3.2.1 Density, porosity and permeability
The average density for a sandstone is 2650 kg/m^3, using a variation of 100 kg/m^3, this results in a range of 2550 to 2750 kg/m^3. Porosity is the ratio of the volume of voids to the total volume. The average porosity value for sandstone is 0.148 (Barrell, 1914). By comparing this data to the porosity range given by (Manger, 1963) and the porosities of sandstone by the various well drillings (Doddema, 2012)(Redjosentono, 2014)(Veldkamp et al., 2015) in the Rotliegend Sand Reservoir, a relative porosity range from 0.1 to 0.3, with a mean of 0.2, is selected.

Permeability characterises the ability of a porous material to transmit a fluid. The permeability grade for a sandstone varies from 10^2 mD for a good aquifer till 10^{-2} mD for a poor aquifer (Bear, 1972). By recognising this, and by taking into account the well drilling data of the Rotliegend Sand Reservoir (Redjosentono, 2014)(Veldkamp et al., 2015), the range of permeability is chosen to be from 50 to 350 mD, with 200 mD as a mean.

3.2.2 Thermal conductivity and specific heat capacity
The thermal conductivity defines the rate at which heat is conducted through a material by characterising the heat flow density as a result of a temperature gradient. The thermal conductivity for a sandstone ranges on average from 2.5 to 3.7 (Schön, 2015), with a mean of 3.1. The specific heat capacity is the amount of heat per unit mass required to raise the temperature by one degree of Kelvin. The specific heat capacity can vary widely from for example 710 (Dezayes et al., 2008) to 1640 Jkg^{-1}K^{-1} (Schön, 2015). With most values fluctuating around the average of 1175 Jkg^{-1}K^{-1} (Botor et al., 2002)(Schön, 2015), using a variation of 200 Jkg^{-1}K^{-1}, this results in a range of 975 to 1375 Jkg^{-1}K^{-1}.

3.3 Process parameters

3.3.1 Injection Temperature
The reinjection of water maintains the reservoir pressure and sustains the well productivity. The injection temperature of this water influences the heat conduction, with a higher or lower temperature gradient, and thus the lifetime of the doublet. The injection temperature range considered is 20 °C to 40 °C.

3.3.2 Well spacing, diameter and flow rate
In 2016, nine geothermal doublets have been realised in the West Netherlands Basin. In most doublets, a well spacing of 1 to 1.5 km should guarantee a life time of at least 30 years (Willems, 2017). In this research, the possibility for a life time of approximately 15 years will be analysed. Because of this, a well spacing of 500 meters will be considered as the minimum well spacing, with a maximum of 1,500 meters. The flow rate of the well is taken at 250 m3/h, with a minimum of 200 and a maximum of 300 m3/h. The diameter of the well at production is 8.5 inch, which is 0.2159 meter.

3.4 Liquid parameters
The fluid injected and produced from the system is water. The fluid properties are defined by COMSOL as temperature dependent functions. The standard formulae provided by COMSOL for water are not questioned or changed. For example, the density of water is defined as:

$$\rho_w = 838.466135 + 1.40050603T - 0.0030112376T^2 + 3.71822313 \cdot 10^{-7}T^3 \tag{11}$$

For which T [K] is the temperature.

All the formulas defining the water properties are provided in the Appendix. Defining the water properties as temperature dependent functions causes the fluid parameters to change by changing other parameters of interest. Viscosity, for example, decreases significantly by increasing temperature, while density changes with a neglectable amount for a given temperature change.

3.5 Overview of parameter solution space

In table 1, the solution space for the reservoir rock, process and surrounding rock parameters are shown.

Parameter	Minimum	Mean	Maximum
Reservoir rock parameters			
Depth [m]	1600	2300	3000
Thickness [m]	20	100	180
Density [kg/m^3]	2550	2650	2750
Porosity [-]	0.10	0.20	0.30
Permeability [mD]	50	200	350
Thermal conductivity [Wm^{-1}K^{-1}]	2.5	3.1	3.7
Specific heat capacity [Jkg^{-1}K^{-1}]	975	1175	1375
Process parameters			
Flow rate [m^3/h]	150	250	350
Injection temperature [$^{\circ}$C]	20	30	40
Well spacing [m]	500	1000	1500
Surrounding rock parameters			
Density [kg/m^3]	1650	1750	1850
Porosity [-]	0.005	0.05	0.095
Permeability [mD]	0.025	0.05	0.075
Thermal conductivity [Wm^{-1}K^{-1}]	1.5	2.0	2.5
Specific heat capacity [Jkg^{-1}K^{-1}]	1150	1250	1350

Table 1: Rock and process parameters used for modelling

4. COMSOL Multiphysics model

COMSOL Multiphysics 5.3a is a finite element software and is used to analyse the geothermal processes and the physical phenomena involved in this study. The *Darcy's Law interface* is used to describe the subsurface flow by implementing both Darcy's Law (equation 1) and the Continuity Equation (equation 2 and 3). Besides, the *Heat Transfer in Porous Media* interface describes the heat exchange inside the model by applying the heat transport equation (equation 5). Both interfaces are bidirectionally coupled, since the material properties of the groundwater are dependent on the temperature, while the heat regulating the temperature is conversely dependent on the subsurface flow due to advection. This chapter describes the choices and assumptions made while defining the model and its geometry, the boundary conditions implemented in these interfaces and the relative tolerance and mesh grid of the base model.

4.1   Geometry model

Initially, the parameters and their influences on the breakthrough time and production temperature were analysed in a 2D model. However, the interfaces in COMSOL Multiphysics consider radial flow instead of laminar flow, which is why the model in 2D calculated unrealistic high pressures resulting in incorrect fluid flows and temperatures. Because of this, the problem is analysed in a 3D model (figure 3). In order to decrease the size of the model and its computation time, the model is symmetrical at opposite sides of the symmetry plane shown in figure 3.
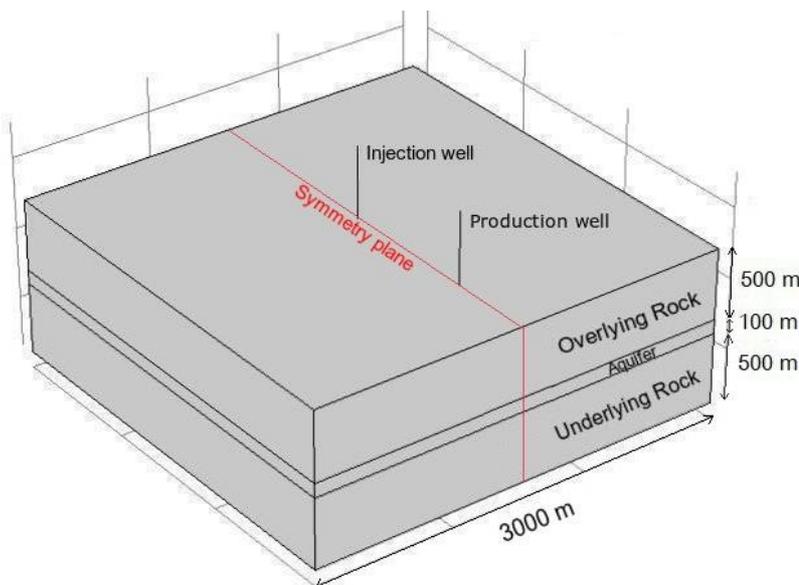
Figure 3: Visual explanation of the base model

As shown in figure 3, the 3D model is displayed as a cuboid divided into 3 layers, the middle layer being the aquifer. As can be seen, the injection and production well are located along the y-axis at the centre of the x- and z-axis. Along this yz-plane, equal to the symmetry plane, the 2D results are analysed as shown in figure 4. Figure 4 represents the base model with a well spacing of 1000 meters. In this base model, the production well and injection well are located respectively 500 and 1500 meters from the model boundaries to make sure that the injection and production well do not interfere with the model boundary conditions. The injected cold water has a higher chance of reaching the boundaries and their conditions, explaining the extra 500 meters from the injection well. As stated in chapter 3, the distance between the wells is a changing parameter and because of this, the edges of the cuboid change in length by changing the well spacing. The length of the cuboid is defined as three times the well spacing, with the production well always placed 500 meters from the model boundary. This causes the injection well to be at least the minimum well spacing (500 meters) away

from the boundary, this distance then increases by increasing the well spacing. The underlying and overlying strata have a thickness of 5 times the aquifer thickness, causing the overall thickness to be 1100 meters for the base model. The wells are modelled as line segments, with only the producing and injecting segments inside the aquifer. The lines drawn above this segment in figure 3 and 4 are for clarity.
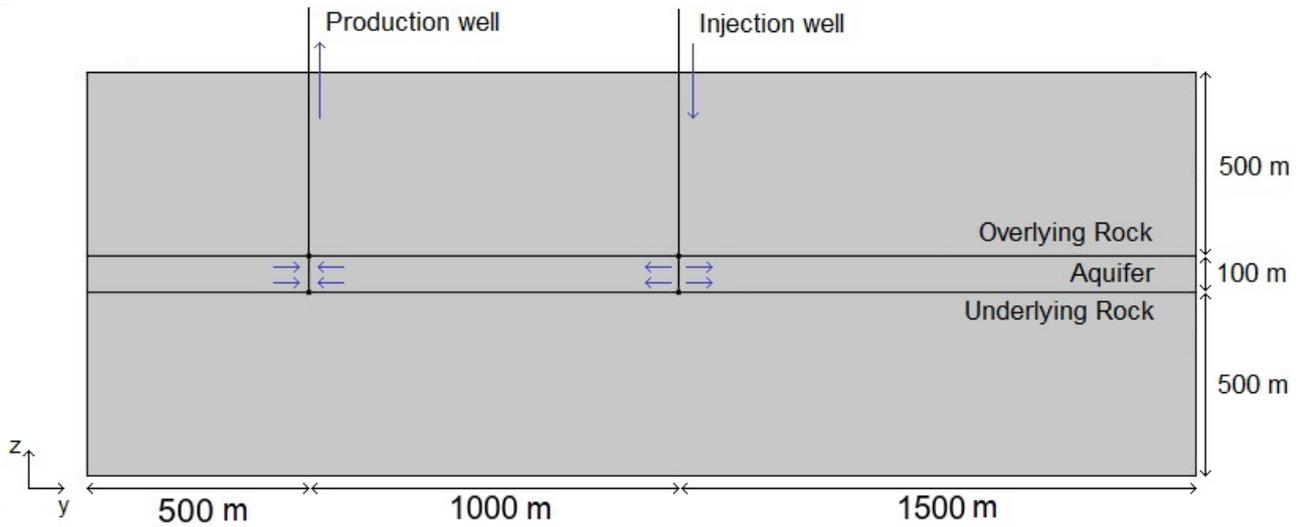
Figure 4: Cross-section of the base model

4.2   Darcy's Law interface

Figure 5 shows a visualisation of the boundary conditions. As can be seen, the cuboid contains 6 outer surface boundaries: 4 vertical and 2 horizontal boundaries. The two horizontal boundaries of the cuboid are considered impermeable. The pressure given by the pore water pressure (equation 10) is applied as a boundary condition at the vertical boundaries, which means that the pressure differs only by height along these boundaries. The fluid flow caused by the injection and production well are modelled using the well feature and are specified as a mass flow rate (equation 4).

4.3   Heat transfer in Porous Media interface

The four (blue) vertical boundaries of the cube have a constant heat supply from the rock formations located at the sides. Because of this, these four boundaries are considered thermally insulated while modelling the heat transfer equation. The horizontal boundaries are defined as open boundaries, which means that both the heat inflow and outflow are dependent on the geothermal gradient. The heat inserted by the injection well is modelled as a line heat source and defined by equation 8.

■ Horizontal boundaries: no fluid flow & open heat boundaries
■ Vertical boundaries: pressure defined & thermally insulated
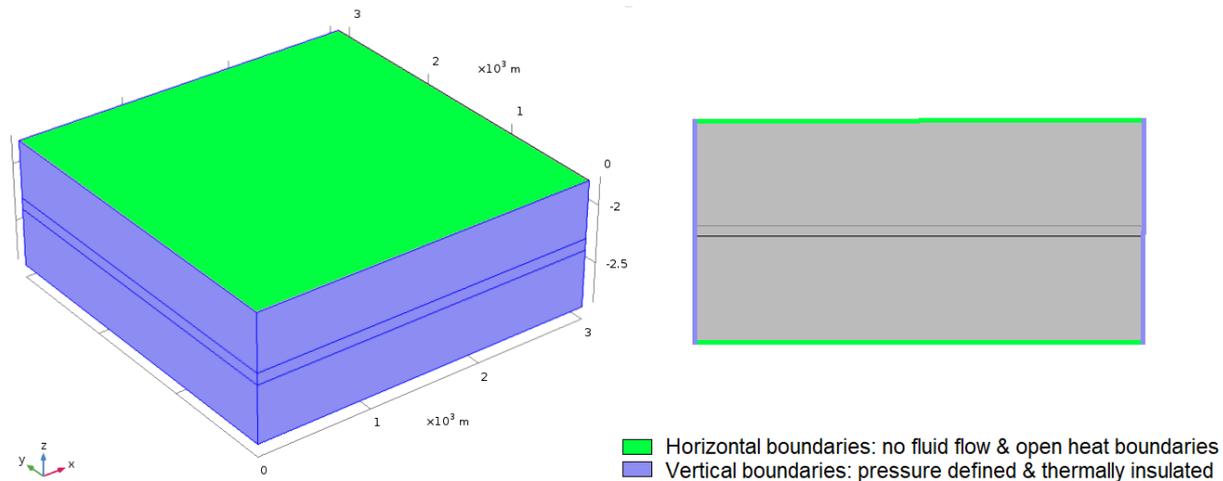
Figure 5: Visualisation of the boundary conditions

4.4 Mesh

Meshing the geometry of the 3D model is of importance to obtain accurate results in the fastest computation time. For a physics-controlled mesh, COMSOL Multiphysics has built-in parameter sets which range from extremely fine to extremely coarse. In this study, the parameter sets extremely fine, fine and normal are used and customized to the geometry. For clarity, the mesh is subdivided in two different domains. One focuses on the aquifer mesh grid, the other one on the overlying and base rock. Because the gradients inside the aquifer are larger and the results inside the aquifer are of more importance for the thermal breakthrough time and production temperature, the grid is refined inside the aquifer with in addition an even finer element size at the well locations. This way, inside the aquifer and specifically close to the wells a higher precision is specified. The maximum element size inside the aquifer is 80 meters, the number of elements at the wells is dependent on the thickness of the reservoir to account for the changing thickness. For the base model, the number of elements distributed along the wells is $10 \cdot round\left(\frac{thickness\ reservoir}{30}\right) = 30$. The two outer layers have a larger element size, since the fluid flow is mostly inside the aquifer, with a refined element size at the vertical boundaries (green in figure 5).
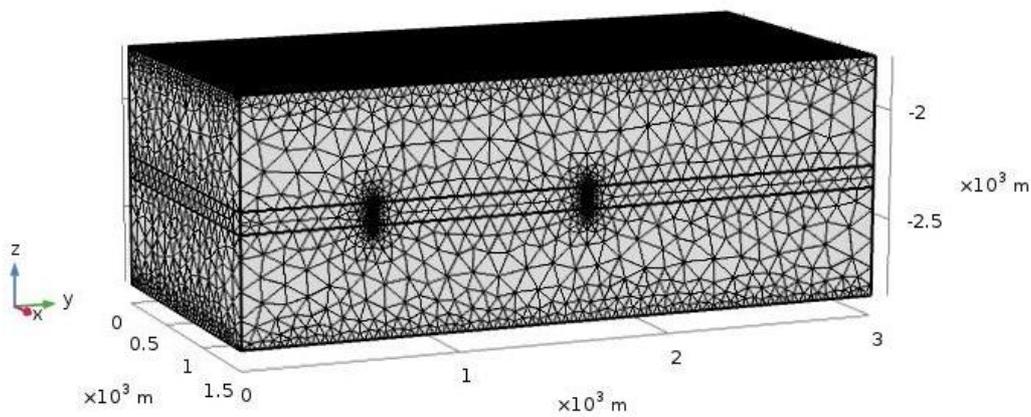
Figure 6: Visualised mesh grid for the base model

5.   Results & Discussion

The results show the effects of the varying values of the parameters on the breakthrough time and the decrease in water temperature at the production well. In order to analyse these results, it is important to discuss the impact of the chosen relative tolerance on the results, which is described in section 5.1. The changes in parameters will be compared with the results of the base model, which are displayed in subchapter 5.2. In subchapter 5.3, the varying values in parameters are visualised over 50 years. In the line graphs (figures a), the blue line indicates the base model, which in every graph is the same. The red line is the minimum and the green line the maximum value of the parameter. In the combination charts (figures b), the columns of the histogram show the breakthrough time in years. On the secondary y-axis, the change in temperature compared to the initial temperature is plotted. For the density, porosity, permeability, thermal conductivity and specific heat capacity the results for the parameter change for the aquifer will be displayed first, followed by the results from the changed parameter for the surrounding rocks. After this, a final relative ranking of the parameters will be determined in subchapter 5.4.

5.1 Significance of relative tolerance

The relative tolerance is related to the convergence criteria and is the maximum amount of error allowed in the solution attempt. The iterative processes within the solver sequence will continue to iterate on the solution attempt until the calculated relative error drops below the pre-specified relative tolerance. Because of this, the larger the relative tolerance, the more the calculated solution diverges from the actual solution due to accumulating errors at each iteration. On the other hand, decreasing the relative tolerance will give an increase in computation time. This requires balancing between the need for a precisely correct answer and the computation time. In figure 7 the results of the base model for three different relative tolerances are shown. As can be seen, there is not only a large difference in breakthrough time and temperature drop, but also in shape. It is therefore important to be aware of the changes in results due to changes in relative tolerance, but it depends on the study if a solution that computes for 1.5 hours (relative tolerance of 0.0001) is even required. In this study, the produced temperature lines for the varying parameter values where interchanging for a relative tolerance of 0.004. As an example, this can be seen in the zoomed-in graph of the porosity values in figure 8. Here, the order of breakthrough time in years from smallest to largest is: 0.20, 0.15, 0.30, 0.10, 0.25. This is an unrealistic order of breakthrough time for this model. Because of this, the decision was made to use an even smaller relative tolerance. The relative tolerance is taken at 0.0001. This relative tolerance is applied to all the simulations and thus their results shown in the following sections.
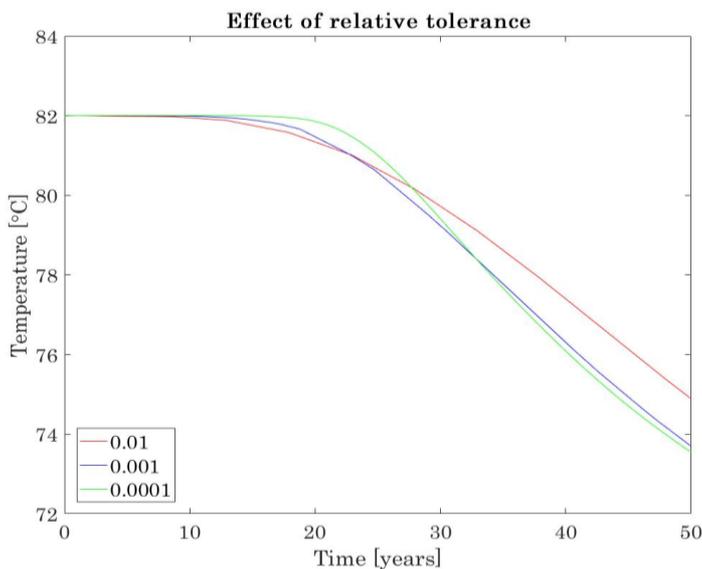
Figure 7a: Effect of relative tolerance on base model   *Figure 7b: Relative tolerance on breakthrough time and temperature drop*
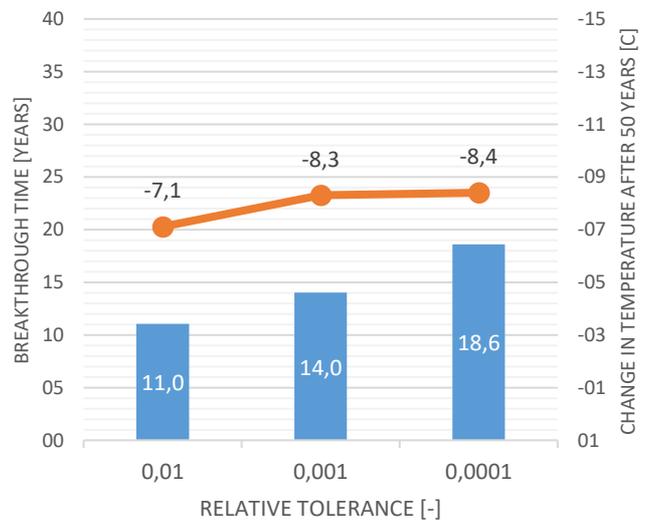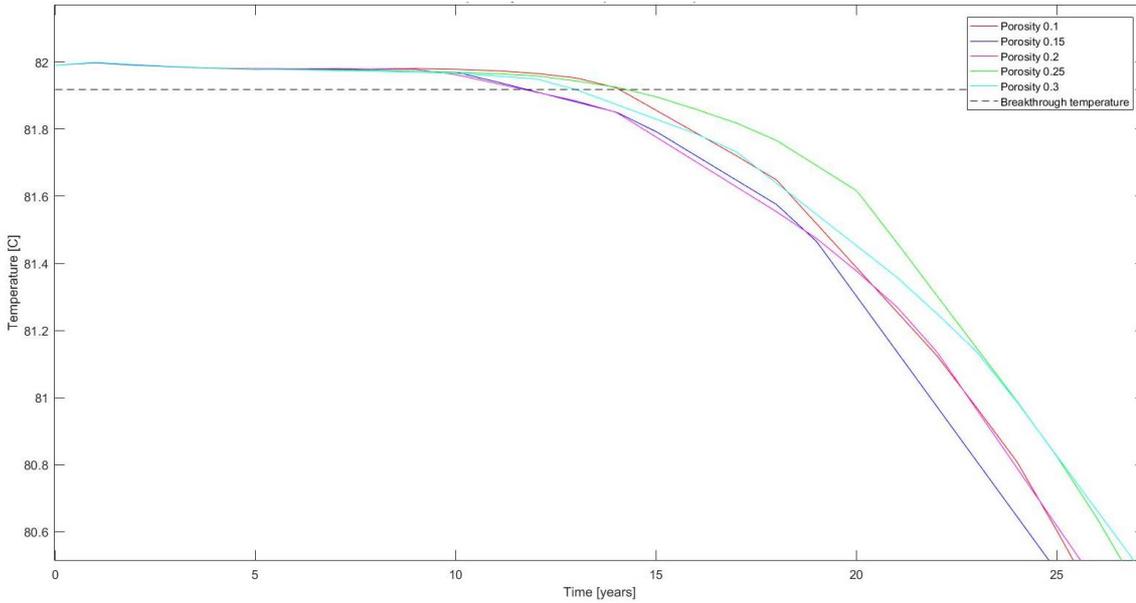
Figure 8: Changing porosity values for a relative tolerance of 0.004

5.2   Base model

The results of the base model, based on the mean values of the parameters in table 1, are shown in the figures below. The colour bar is applicable for all figures. The streamlines in figure 13 and 14 are represented by white lines and are only visualised inside the aquifer. On this base model, the uncertainty analysis is carried out and the changes in breakthrough times are always in comparison with this model. As can be seen, the water propagates mainly through the aquifer and reaches the production well before 25 years. The radial flow of water due to pumping and injection is visualised quite clearly in figure 13 and 14, which explains the relatively slow drop in temperature at the production well.
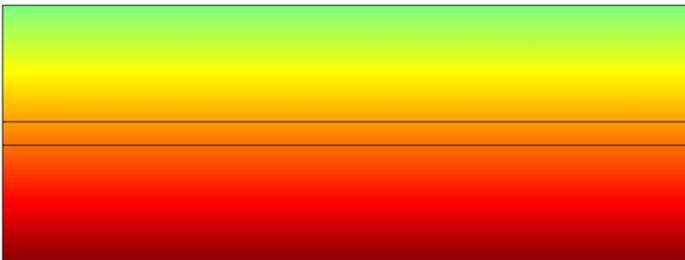
Figure 9: Base model at t = 0
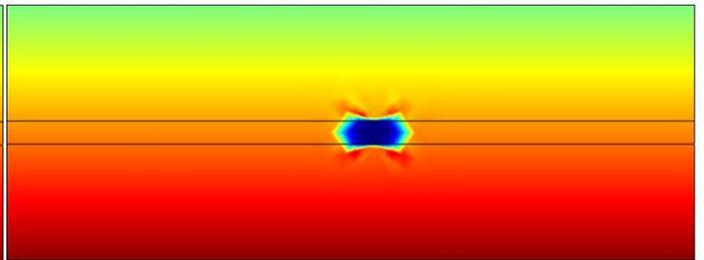
Figure 10: Base model at t = 1 year
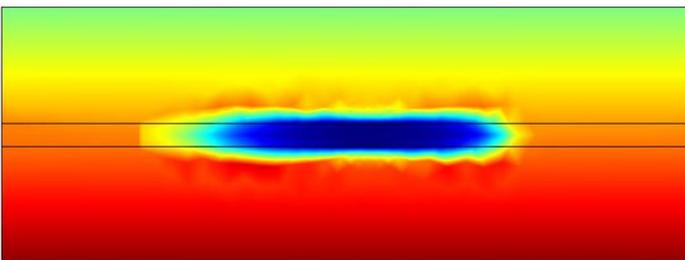
Figure 11: Base model at t = 25 years
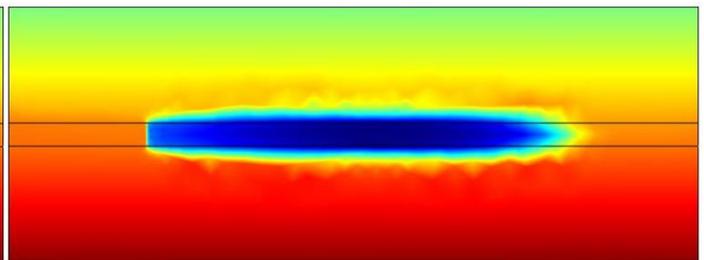
Figure 12: Base model at t = 50 years
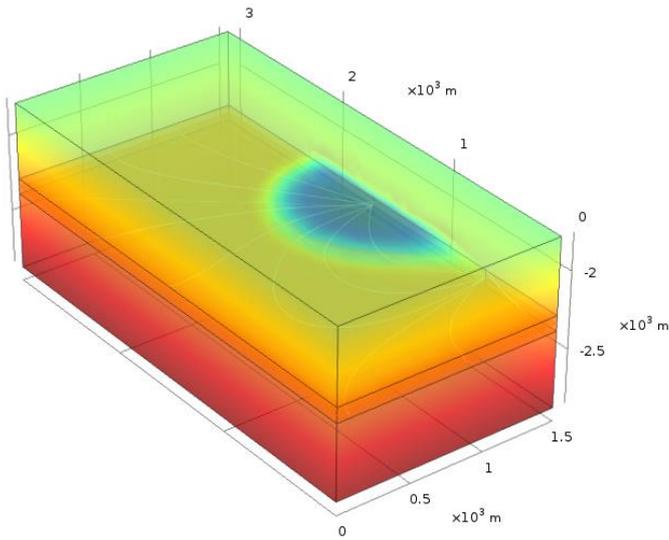
Figure 13: Base model at t = 25 years
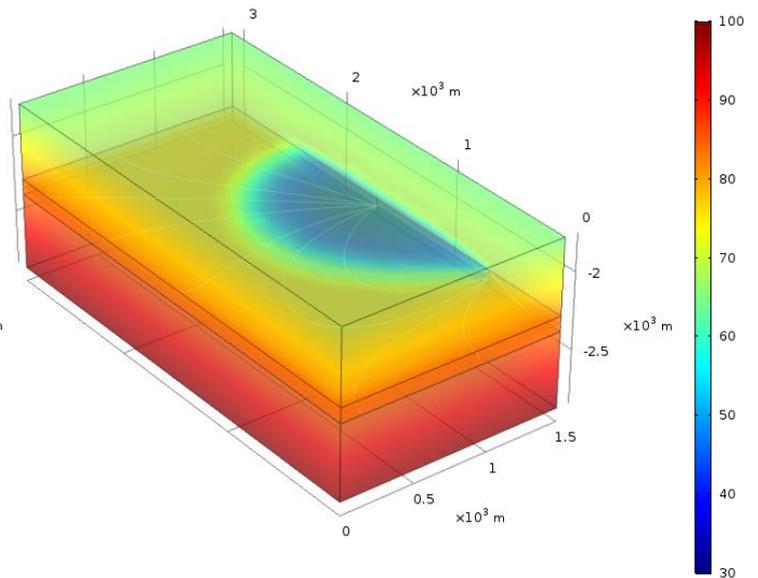
Figure 14: Base model at t = 50 years

5.3   Rock parameters

The investigated rock parameters are: depth, thickness, density, porosity, permeability, thermal conductivity and specific heat capacity. The results of each parameter will be discussed separately.

5.3.1   Depth
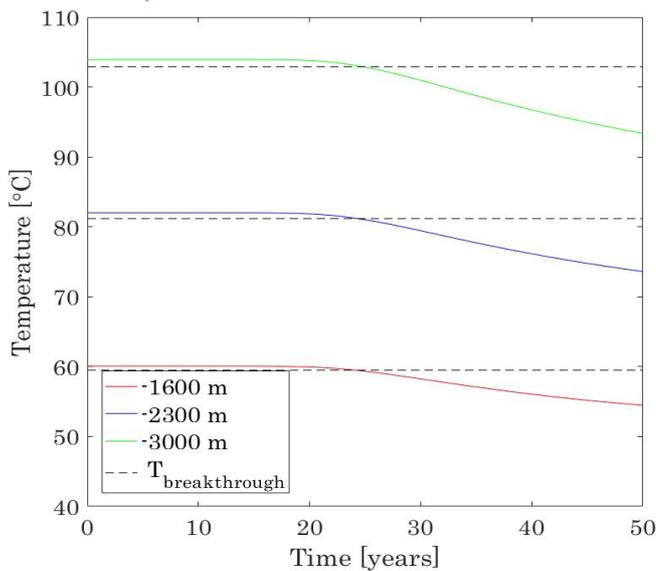
Figure 15a: Effect of depth on produced water temperature
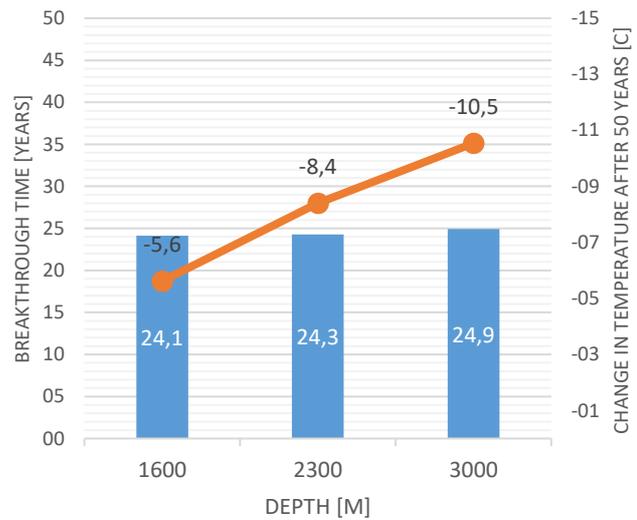
Figure 15b: Breakthrough time and temperature change

Figures 15a and 15b show that the depth of the reservoir has minimal to no effect on the thermal breakthrough time. A slight increase can be seen for an increase in depth, while it does have a significant, almost linear, effect on the temperature decrease over time.

The increase in change in temperature from -5.6 °C at 1600 meters depth to -10.5 °C at 3000 meters depth can be related to Newton's law of cooling. Newton's law of cooling states that the rate of heat transfer from an object is proportional to the difference in temperature between the object and its surroundings. This indicates that the increased temperature difference between the constant injected temperature of 30°C and the temperature of the water initially in place due to the increase in depth causes the heat loss to increase proportionally. Due to the higher amount of heat loss, the temperature of the water at the production well decreases with a faster rate.

Based on Newton's law of cooling the slight increase in breakthrough time by increasing the depth is unexpected. It would be more realistic for the breakthrough time to increase, coherent to the decrease in temperature change. Another reason for the breakthrough time to decrease instead of increase would be the viscosity of water. The viscosity of water decreases significantly with increasing temperature, which based on Darcy's law, would imply a faster velocity and thus a shorter breakthrough time. The unexpected increase in breakthrough time can be explained by a possible accuracy error, since the breakthrough times are all very close to each other. For example, the largest difference in breakthrough time is only 0.8 years for a change in depth from 1600 to 3000 meters.

5.3.2 Thickness
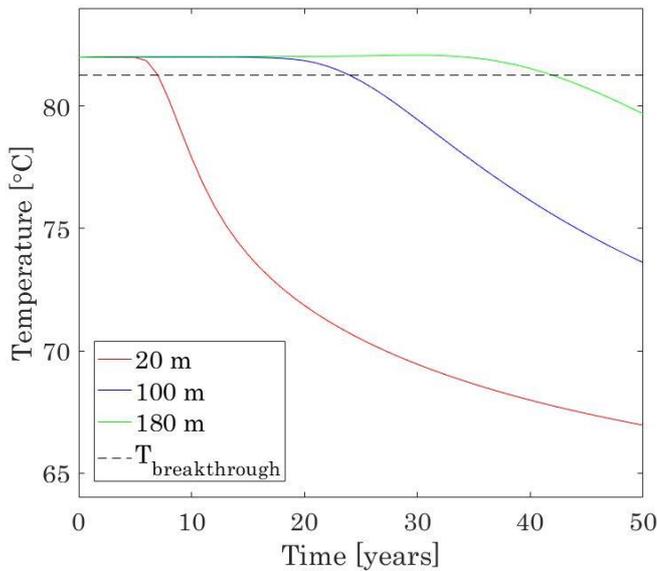
Figure 16a: Effect of thickness on produced water temperature   Figure 16b: Breakthrough time and temperature change
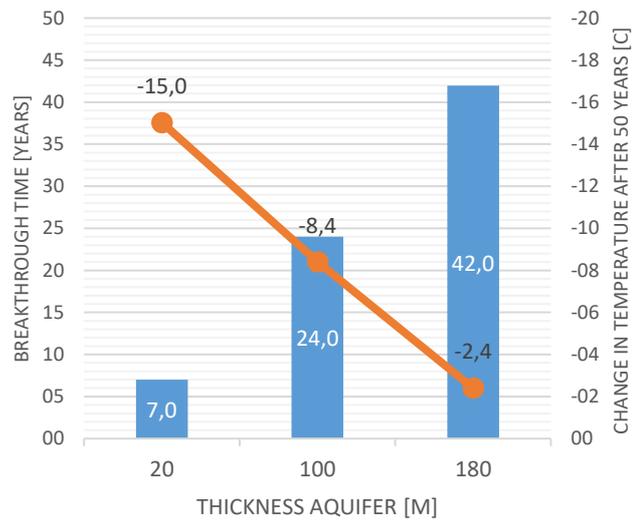
As can be seen in figure 16a and 16b, the thickness of the aquifer has a significant effect on the breakthrough time and the temperature decrease. Increasing the base model thickness to 180 meters, gives an increase in breakthrough time of 18.0 years and a decrease in temperature change of 6.0 °C.

The increase in breakthrough time and the smaller temperature drop at the production well by increasing the aquifer thickness can be explained in two ways. Firstly, since the porosity remains the same, the reservoir volume from which the heat is extracted is increased by increasing the thickness. This means that the ratio of the injected cold water to the overall (warm) reservoir body becomes smaller. Since the specific heat capacity of the rock is constant, the temperature of the produced water is lowered more slowly. This means that the amount of thermal energy produced decreases more slowly and thus the total thermal energy production increases. Secondly, since the flow rate (250 m³/hour) is constant and the reservoir water volume increases, the circulation time increases. The longer circulation time causes the water to be in contact longer with the reservoir rock, which enhances the exchange of temperature and will cause the temperature to decrease less over time. These two effects together cause the thickness to have a greater effect on the breakthrough time and temperature drop than the other reservoir parameters.

5.3.3 Density
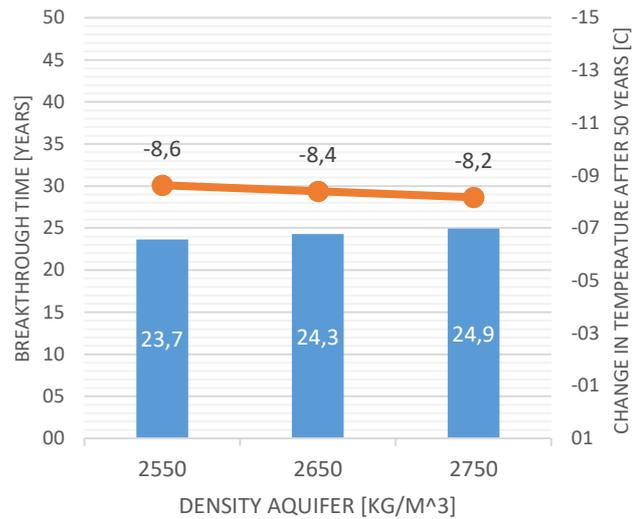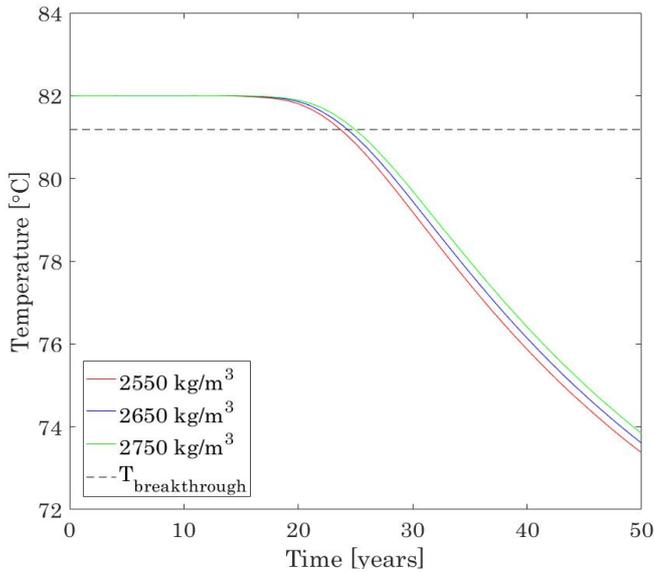
Figure 17a: Effect of aquifer density on produced water temperature

Figure 17b: Breakthrough time and temperature change
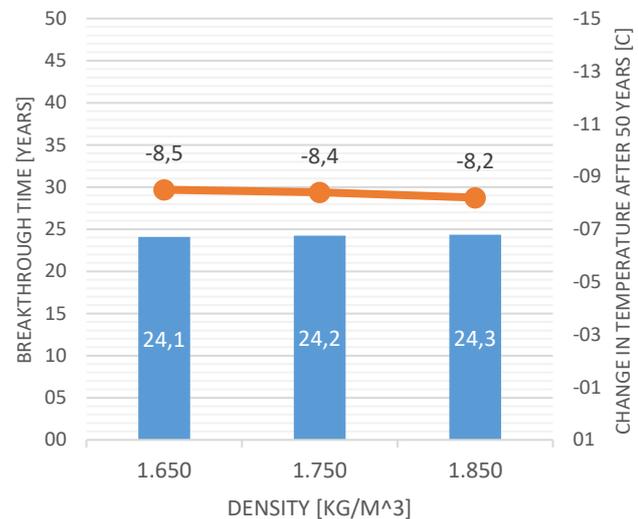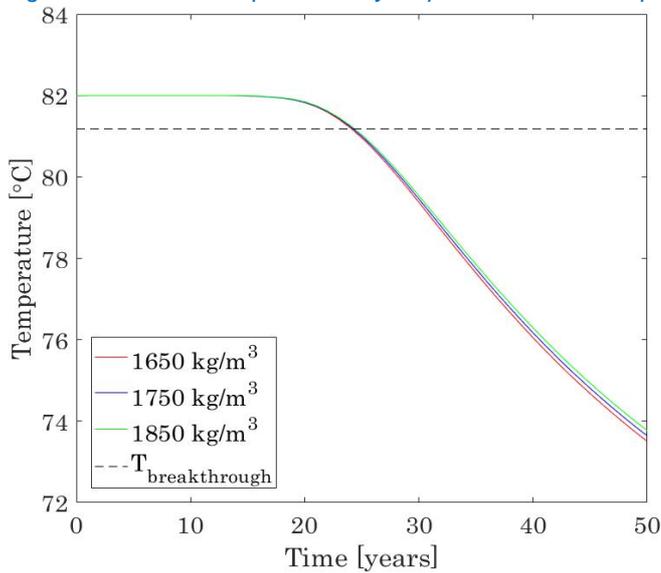
Figure 18a: Effect of surrounding rock density on produced water temperature Figure 18b: Breakthrough time and temperature change

Figure 17 and 18 demonstrate the results of the change in density for the aquifer and the surrounding rocks respectively. For the reservoir and the surrounding rocks, the density only has a small effect on the breakthrough time and the temperature change. An increase in density for the reservoir rock and surround rocks give a slight decrease in change in temperature after 50 years for both the reservoir rock and surrounding rocks (0.4 °C and 0.3 °C respectively). Besides, an increase in density gives a slight increase in thermal breakthrough time for both the surrounding and the reservoir rock.

The specific heat capacity is defined as the total heat capacity divided by the density and volume. Since the specific heat capacity and volume remain the same, an increase in density will give an equal relative (%) increase in heat capacity. As mentioned at the change in thickness (volume), it therefore takes more energy and thus time to decrease the rock with one degree, which gives an increase in thermal breakthrough time (it takes longer to reach the production well) and a smaller decrease in temperature.

5.3.4 Porosity
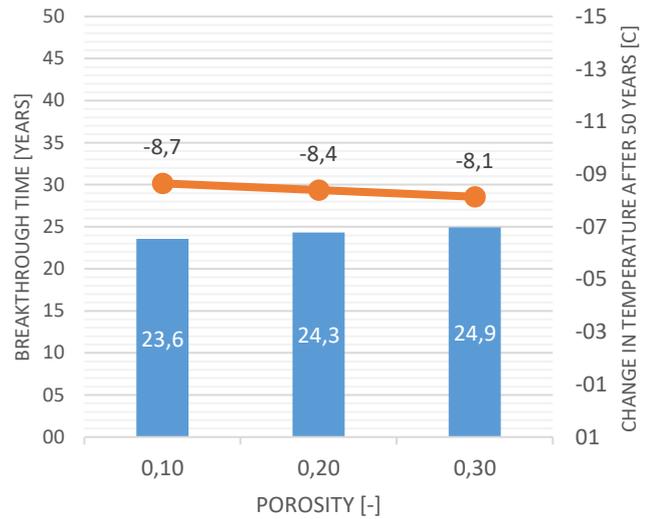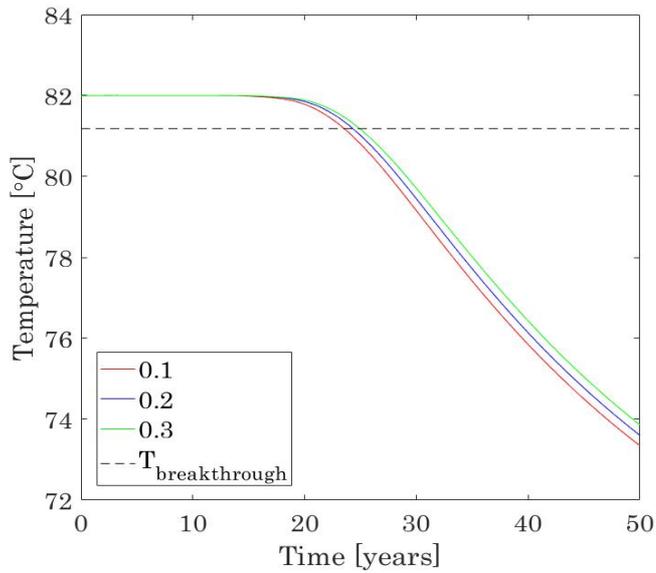
Figure 19a: Effect of reservoir rock porosity on produced water temperature

Figure 19b: Breakthrough time and temperature change
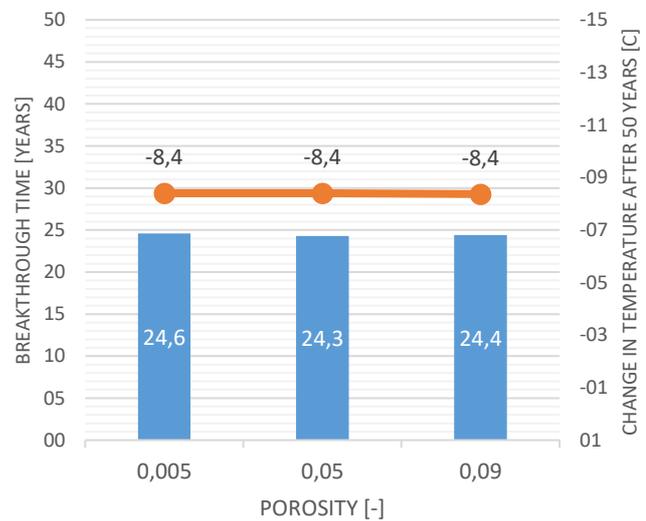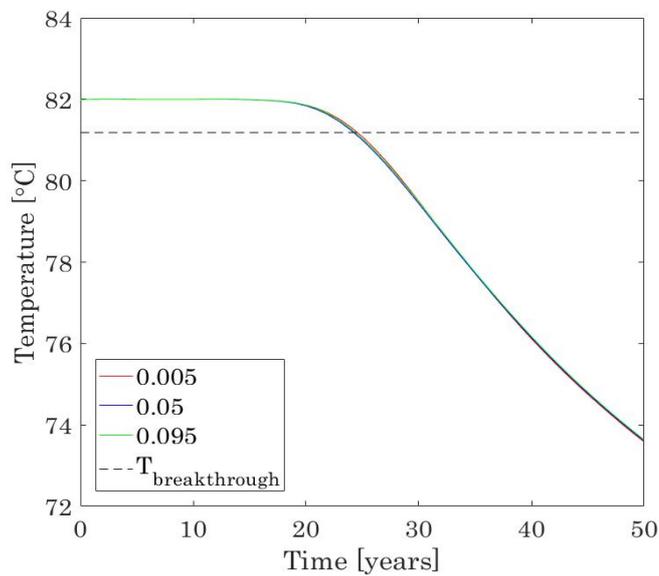
Figure 20a: Effect of surrounding rock porosity on produced water temperature

Figure 20b: Breakthrough time and temperature change

Figures 19 and 20 show the results for the change in porosity for the aquifer and the impermeable surrounding layers respectively. For the reservoir porosity, a small increase in breakthrough time is visible for a higher porosity value (1.3 years for an increase in porosity of 0.2) and a small decrease in temperature change (0.6 °C for an increase in porosity of 0.2). For the porosities of the surrounding layers, the change in value has no to minimal effect.

To prevent repetition, the explanation for the effects of these changes are written as the two arguments for the thickness explanation at page 20. There it is explained that the increase of the volume of water has an influence on the circulation time and the ratio between heated rock volume and cold injected water. As can be seen, there is a large difference in size of the impact between the thickness and the porosity. This can be explained by the fact that for an increase in thickness the ratio between the water body and the reservoir rock remains the same, while for an increase in porosity this ratio increases. Due to the increase in ratio, the volume of rock per volume of water decreases, which means that a smaller portion of rock is transferring heat to the water, resulting in a larger decrease in temperature.

5.3.5 Permeability
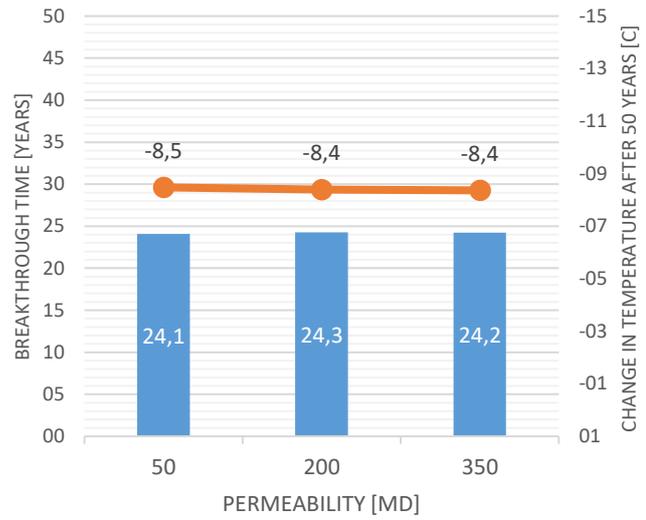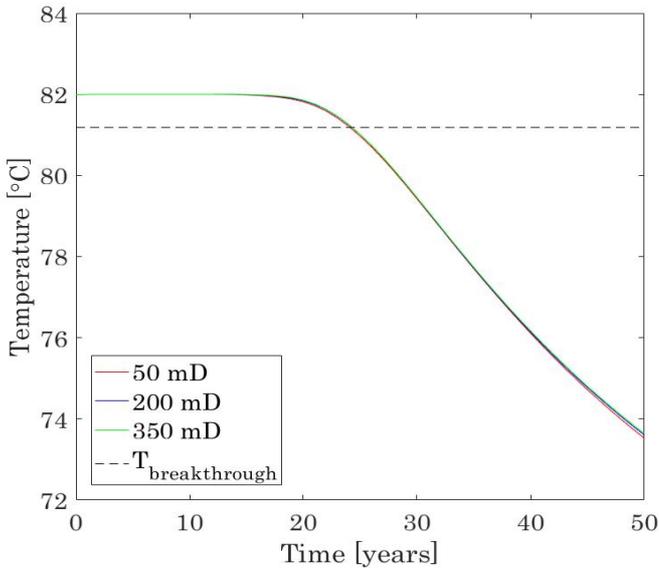
Figure 21a: Effect of permeability on produced water temperature

Figure 21b: Breakthrough time and temperature change
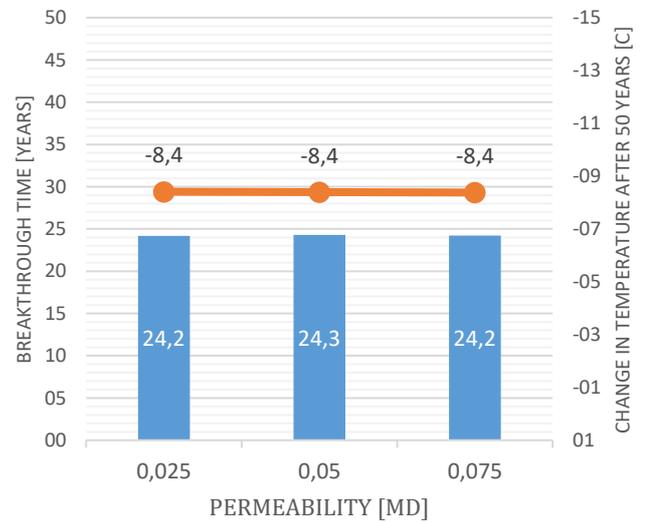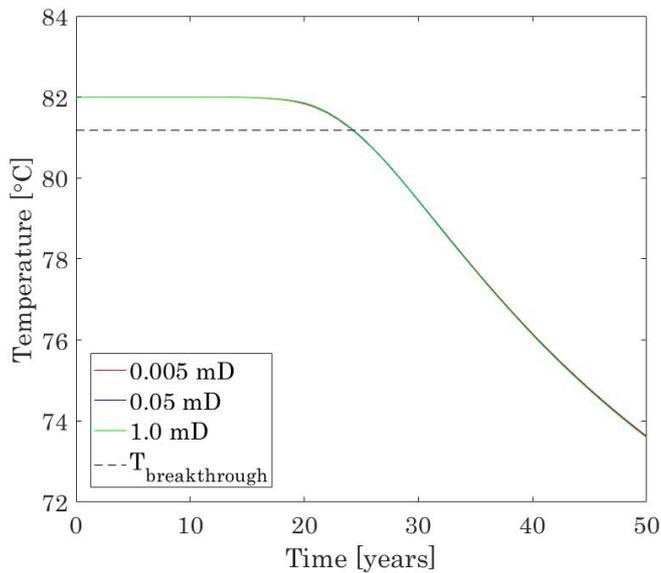
Figure 22a: Effect of surrounding permeability on produced water temperature Figure 22b: Breakthrough time and temperature change

As can be seen, the permeability has minimal to no effect on the breakthrough time and the temperature decrease over the years. This is because the produced flow rate is held constant and is mass-defined. Based on Darcy's law (equation 1), this causes a change in permeability to give an equal change in pressure, which causes the impact of the change in permeability to cancel out.

In other research, for example in the report of Ganguly, et al. (2017), the permeability has a noticeable impact on the breakthrough time and temperature drop. This is because the permeability is the ease with which a fluid flows through a porous media, which influences the flow velocity and consequently the time that it takes for the injected fluid to reach the production well. Besides, the increase in flow velocity due to an increase in permeability would decrease the circulation time and decrease the exchange of temperature between the reservoir rock and the fluid.

5.3.6 Thermal conductivity
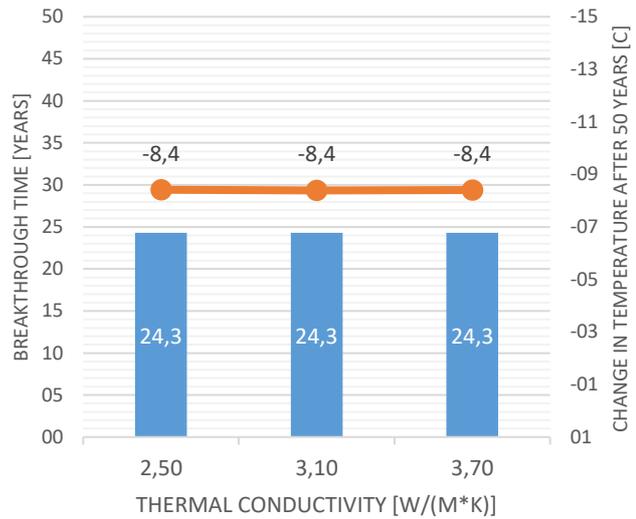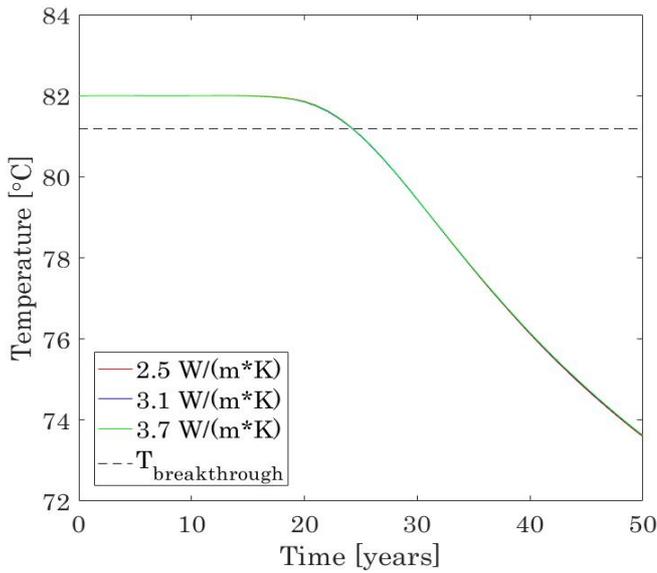
Figure 23a: Effect of reservoir rock thermal conductivity on produced water temperature   Figure 23b: Breakthrough time and temperature change
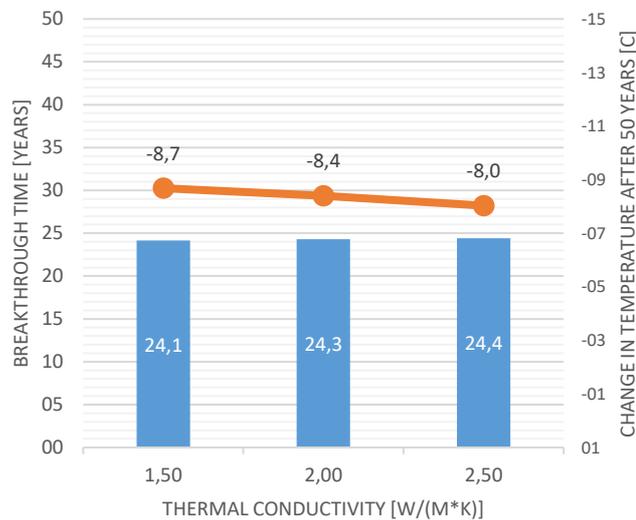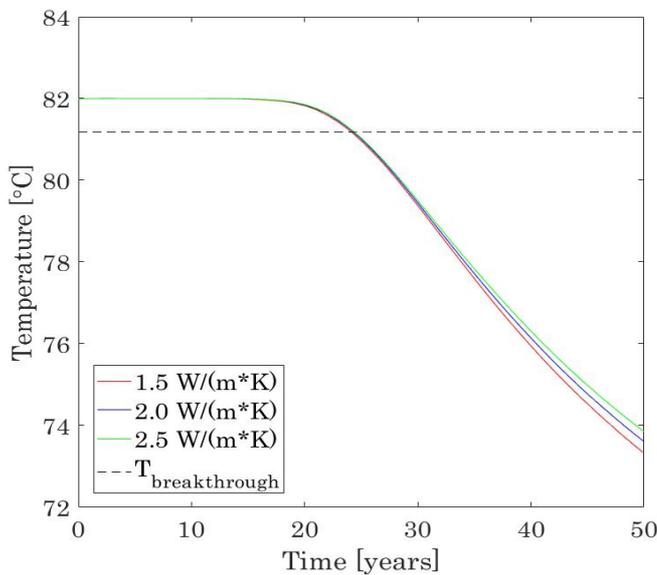
Figure 24a: Effect of surrounding rock thermal conductivity on produced water temperature   Figure 24b: Breakthrough time and temperature change

Heat is extracted at a constant rate from the reservoir. At the same time, heat is transferred from the surrounding rocks to the reservoir by conduction. If the thermal conductivity of the aquifer or the surrounding rocks is higher, the rate of heat transfer increases, thus the rate of recharging the rock's temperature increases. Because of this, the aquifer's temperature decreases less, and the amount of heat discharged to the circulating water remains higher, with also the temperature of the production water remaining higher. This can be seen for the surrounding rocks (figure 24), where the temperate change indeed becomes smaller with a higher thermal conductivity. However, the temperature change does not differ for the different values of reservoir rock thermal conductivity (figure 23). This is because inside the aquifer convection is the most dominant heat transport mechanism. Because of this, the conduction and thus the thermal conductivity have no to minimal effect on the temperature inside the aquifer. On the other hand, the most dominant heat transport mechanism in the surrounding layers is conduction. Because of this, the impact of the changes in thermal conductivity of the surrounding rocks is higher compared to the impact of the changes in thermal conductivity of the reservoir

The thermal breakthrough time is dependent on the fluid flow velocity inside the aquifer and on the convective heat transfer. Because of this, the thermal breakthrough time is for both the aquifer (figure 23) and the surrounding rocks (figure 24) almost constant when the thermal conductivity changes.

5.3.7 Specific heat capacity
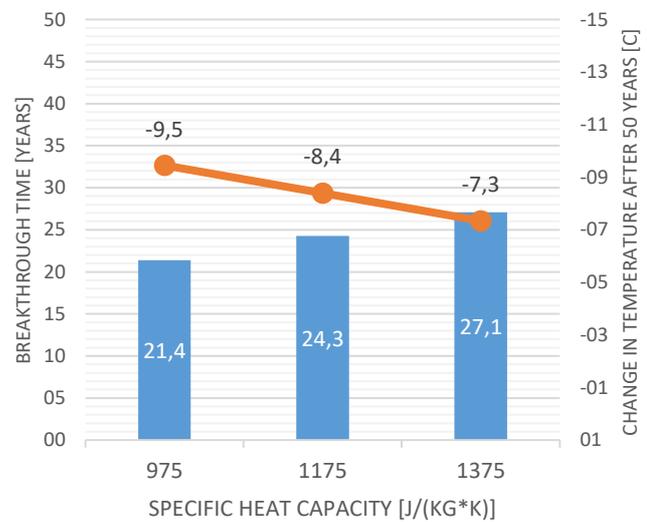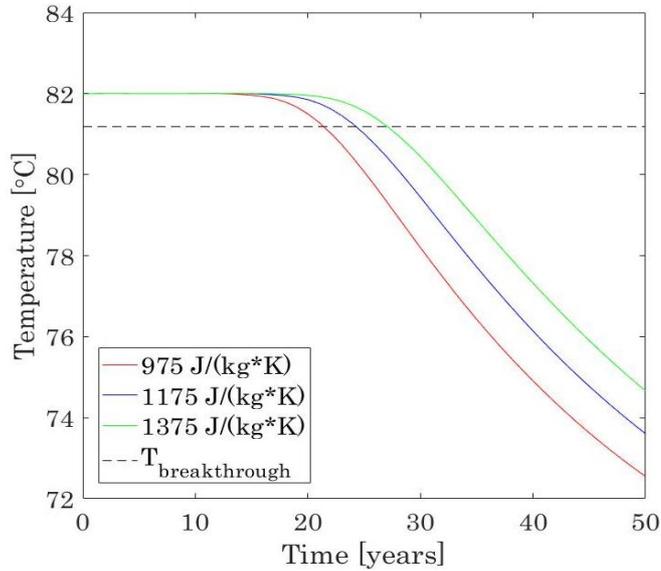
Figure 25a: Effect of reservoir rock specific heat capacity on produced water temperature   Figure 25b: Breakthrough time and temperature change
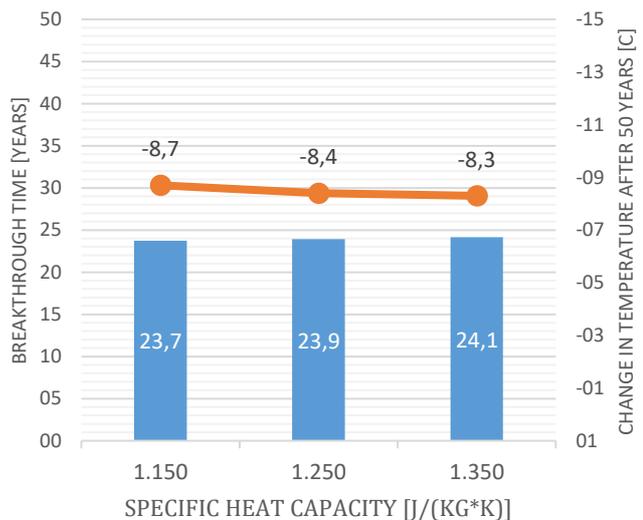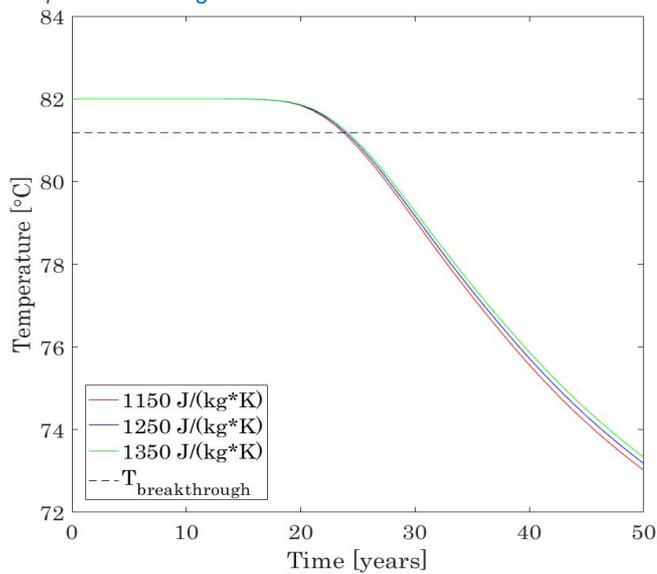
Figure 26a: Effect of surrounding rock specific heat capacity on produced water temperature   Figure 26b: Breakthrough time and temperature change

Increasing the specific heat capacity gives an increase in thermal breakthrough time and a decrease in the change in temperature after 50 years. The change in specific heat capacity of the aquifer has a notably larger impact on the produced water temperatures and breakthrough time than the change in specific heat capacity of the surrounding rocks.

The specific heat capacity is defined as the total heat capacity divided by the density and volume. Since the density and the volume are constant, this results in an increase in overall heat capacity. As mentioned before, this gives an increase in breakthrough time and a smaller decrease in temperature. The difference in impact can be explained by the fact that the temperature decrease of the surrounding rocks is less important than the temperature decrease of the aquifer, since the circulating water is in direct contact with the aquifer rock.

5.4 Process parameters

The investigated process parameters are: flow rate, injection temperature and well spacing. The results of each parameter will be discussed separately.

5.4.1 Flow rate
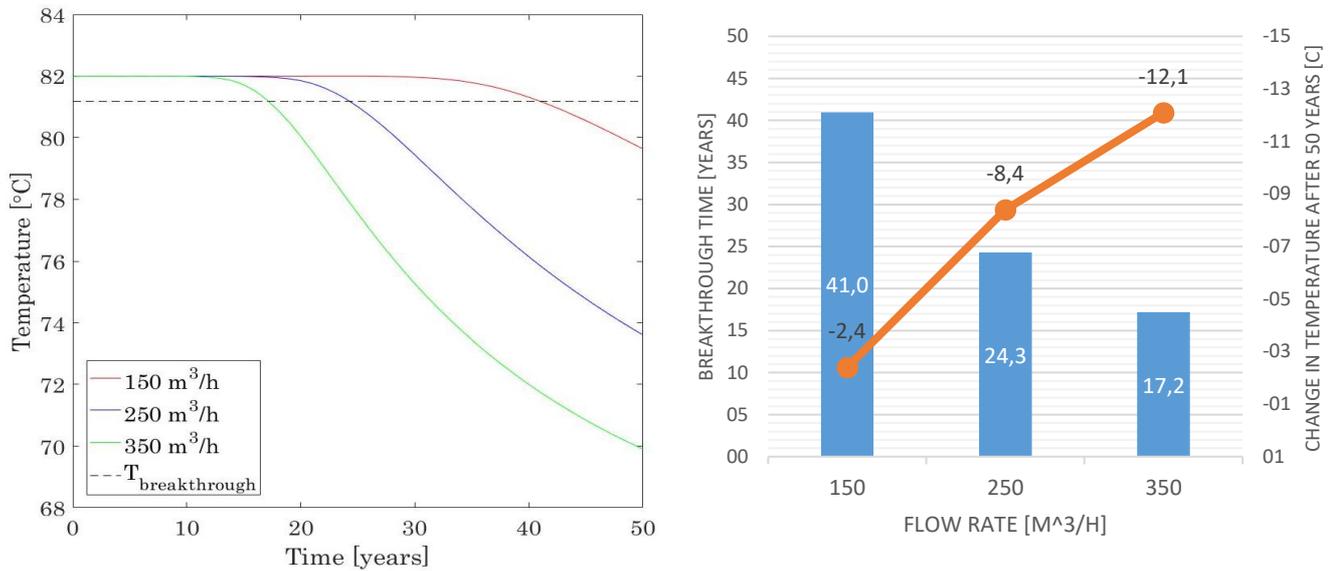
Figure 27a: Effect of flow rate on produced water temperature   Figure 27b: Breakthrough time and temperature change

The results of the variation in flow rate are shown in figures 27a and 27b. The flow rate impacts the forced fluid flow, mentioned in Darcy's law (equation 2 and 3), and the rate at which the convective heat transfer occurs. Since the flow rate is not pressure defined, the changes in pressure due to a higher flow rate are not considered.

As can be seen, an increase in flow rate has a decreasing impact on the thermal breakthrough time and creates a larger decrease in temperature. An increase in flow rate causes the forced fluid flow (equation 2 and 3) to move faster, which increases the rate of circulation of the water. An increase in flow rate also means that a larger amount of cold water is added to the aquifer, this larger volume of cold water has a density difference with the water initially in place and thus adds to the Buoyancy effect. Both increases in fluid flow mechanisms, cause an increase in rate at which the cold water will be diffused with the initially warm water. Besides, if the water passes through the reservoir more quickly, the time that the water is in contact with a certain surface area of the reservoir rock decrease. Assuming the temperature difference between the fluid and the rock and the heat transfer coefficient to be constant over a certain surface area of the rock, the time that it takes for the water to reach a new thermal equilibrium with the rock surface is also constant. Since the fluid flow is increased, the time that the water is in contact with the surface decreases due to the increase of flow rate. This can cause the fluid to not reach thermal equilibrium with the surface, which will cause a more rapid temperature drop.

Besides the increase in fluid flow, the larger volume of cold water added to the aquifer causes the ratio of the injected cold water to the overall (warm) water body to become larger. This causes the fluid to be cooled down faster by convective heat transfer.

5.4.2 Injection temperature
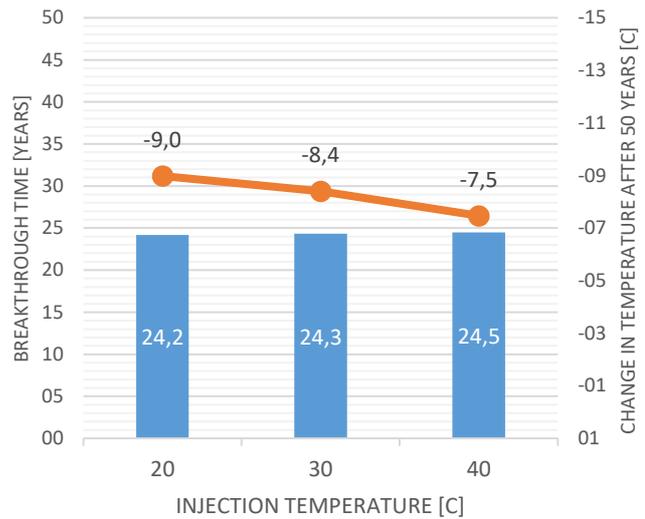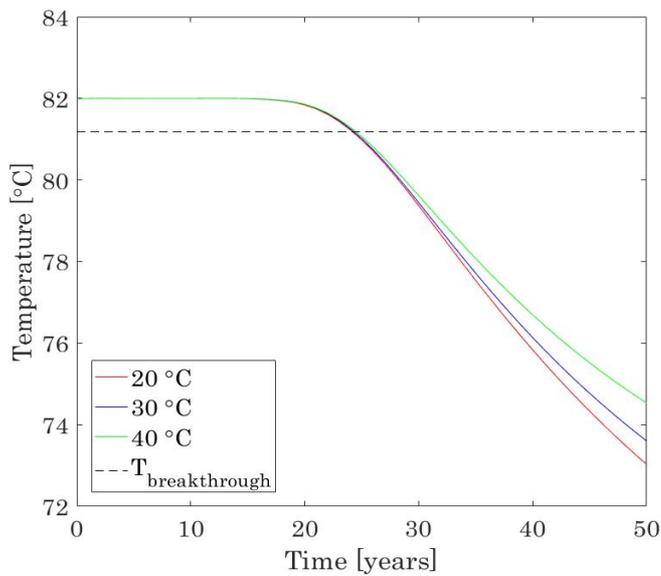
Figure 28a: Effect of injection temperature on produced water temperature Figure 28b: Breakthrough time and temperature change

As can be seen in figure 28a and 28b, the injection temperature has a small impact on the temperature decrease over time (from 30 to 40 °C gives a 0.9 °C temperature change), and an even smaller influence on the breakthrough time (0.2 years between 30 to 40 °C).

The lower the temperature injected, the larger the temperature difference between the aquifer and the fluid, and the larger the heat transfer between the reservoir rock and the fluid (equation 6 and 7). This increase in heat transfer will result in an increase of heat loss and a faster cooled rock and water. This is the same explanation as the reason for the rate of temperature decrease at a lower depth.

Besides, the injection temperature also defines the minimum temperature present in the aquifer. Within the 50 years of the simulation time, the minimum produced temperature does not go below 72 degrees. This is not even close to the minimum temperature present of 20-40 degrees and because of this, this currently does not have an impact. However, if the model would have been analysed over a longer period, this could influence the lowest temperature observed at the production well.

5.4.3 Well Spacing
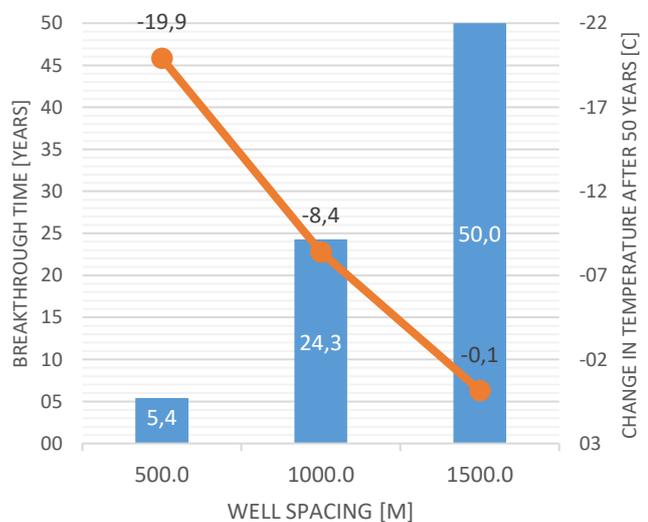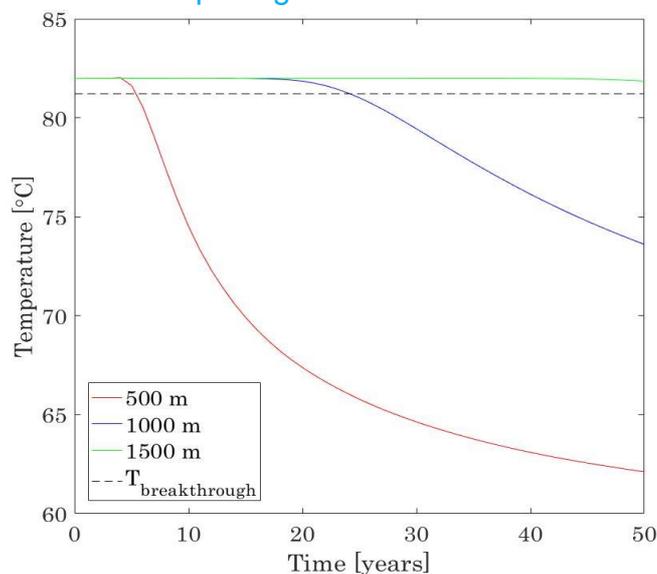
Figure 29a: Effect of well spacing on produced water temperature   Figure 29b: Breakthrough time and temperature change

It is visible in figure 29a and 29b that changing the well spacing has a significant impact on the breakthrough time and temperature drop. An increase in spacing from 1000m to 1500m gives an extra 25.7 years before the cold-water front reaches the production well. This difference in years could be even higher, since the 1500 meters well spacing did not reach the breakthrough temperature within the time range of 50 years. Besides, a well spacing of 1,500 meters only has a temperature decrease of 0.1 C after 50 years. This can be explained by the fact that an increase in well spacing gives the cold water a larger distance to travel and thus a larger volume of rock from which to extract heat before reaching the production well. Since the permeability and flow rate remain the same, this will increase the time for the cold water to be in contact with the rock. This will cause the temperature to decrease less over time. Besides, an increase in length also gives an increase in the volume of water. As explained before, this also adds to the smaller decrease in water temperate.

5.5   Relative ranking of parameters
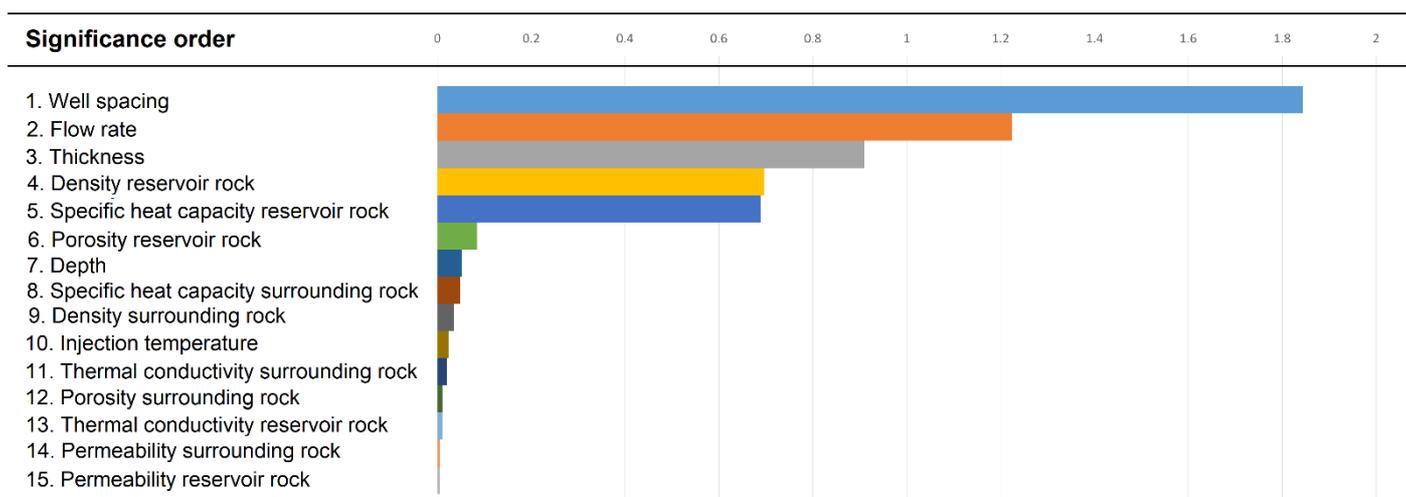
Figure 30: Order of significance for the effect of a proportional change of a single parameter on the breakthrough time.

Figure 30 shows the relative ranking of the parameters. This order is based on the significance of the impact of a proportional change (%) of a single parameter on the breakthrough time (%). The changes are calculated with respect to the base model. The values on the x-axis (0 to 2) show for example that increasing the well spacing from 1000 to 1500 meters (50%) would almost give an increase in breakthrough time of 100% (so would double the breakthrough time). As can be seen, the three parameters that have the most impact on the breakthrough time are the thickness of the aquifer, the flow rate and the well spacing. Between these three, the well spacing has the largest impact.

6. Conclusion

A coupled three-dimensional model is built in COMSOL Multiphysics 5.3 to provide a relative ranking of the parameters that control the thermal breakthrough time of a geothermal doublet. The varying reservoir, process and surrounding rock parameters are each modelled for a minimum, mean and maximum value. The resulting produced thermal water temperatures and breakthrough times are analysed and discussed, and a final relative ranking of significance is provided.

Based on the simulation results, the thickness, flow rate and the well spacing are the reservoir and process parameters that have the largest influence on the breakthrough time. The flow rate has the greatest impact, with a decrease of 16.7 years between a flow rate of 150 m^3/hour and 250 m^3/hour.

The surrounding rock parameters have a notably smaller impact on the breakthrough time than the reservoir rock and process parameters. The surrounding rock parameter with the relatively biggest impact on the breakthrough time is the specific heat capacity, followed by the thermal conductivity. The largest impact of the surrounding rocks is only 0.2 years between a specific heat capacity of 1150 and 1250 $Jkg^{-1}K^{-1}$.

7. Recommendations

Based on the findings and limitations of this research, further research on the effect of the varying parameters on the breakthrough time is recommended. In this research, the simulated solutions where modelled in a three-dimensional model in COMSOL Multiphysics 5.3. The fluid and rock parameters within this model where assumed to be isotropic and the geological units were considered as parallelograms.

This report recommends further research to expand the relative ranking of the parameters by also considering anisotropic conditions of realistic geological settings. This could include permeability distributions for the reservoir rock and taking into account possible faults and fractures. In addition, the effect of pressure on the breakthrough time of the wells could be analysed, by defining the injection and production of the wells by a pressure flow instead of a constant mass flow. This way, the effect of permeability on the breakthrough time could be analysed. Besides that, it would also be interesting to correlate the results of this research to the economic feasibility of a geothermal project and the energy production.

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Appendix: Water properties formulas

Dynamic viscosity

For 273.15 < T < 413.5:

$\mu = 1.3799566804 - 0.021224019151T + 1.3604562827 \cdot 10^{-4} \, T^2 - 4.64540903191 \cdot 10^{-7}T^3$
$+ \, 8.9042735735 \cdot 10^{-10}T^4 - 9.0790692686 \cdot 10^{-13}T^5 + 3.8457331488 \cdot 10^{-16}T^6$

For 413.15 < T < 553.75:

$\mu = 0.00401235783 - 2.10746715 \cdot 10^{-5}T + 3.85772275 \cdot 10^{-8}T^2 - 2.39730284 \cdot 10^{-11}T^3$

Specific heat capacity

$C = 12010.1471 - 80.4072879T + 0.309866854T^2 - 5.38186884 \cdot 10^{-4}T^3 + 3.62536437 \cdot 10^{-7}T^4$

Density

$\rho_w = 838.466135 + 1.40050603T - 0.0030112376T^2 + 3.71822313 \cdot 10^{-7}T^3$

Thermal conductivity

$\lambda = -0.869083936 + 0.00894880345T - 1.58366345 \cdot 10^{-5}T^2 + 7.97543259 \cdot 10^{-9}T^3$