Disclaimer

Doublet Spacing in the "Delft Aardwarmte Project"

BSc thesis report
C.A. den Boer
Student TU Delft
t1282875
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Abstract:
In the "Delft Aardwarmte Project" cooled geothermal water is planned to be injected back into the producing formation. This paper describes the mechanisms occurring during injection and the prediction of the thermal breakthrough that are studied using a reservoir simulation model developed for the "Delft Aardwarmte Project" field properties. Using COMSOL it is shown that flow driven by the density difference between the cold injected water and the warm reservoir water occurs but is not expected to give large errors in production temperature prediction.

Furthermore, numerical simulations of fluid flow and heat transfer between the doublet in the reservoir where performed using COMSOL. It was found that the currently planned 2000 meters will give the first temperature change in the production well after about 44 years. Considering the lifetime of the wells is about 30-40 years this spacing would be more than enough. A more optimal spacing between the wells would be between 1500 and 1600 meters. The use of temperature dependent rock and fluid properties give the same thermal breakthrough time but a more favorable post-breakthrough behavior, in terms of a higher temperature for a longer period.

Heterogeneous aspects are expected to be the key for more accurate temperature prediction as the thermal front movement follows the fluid flow with a certain lag. The combination of heterogeneity and temperature dependant fluid properties was analyzed. It was found that viscous crossflow can occur retarding the thermal breakthrough.

1. Introduction

World population growth and the economic growth of upcoming countries, mainly in Asia, are greatly increasing the world-wide demand for energy. This in combination with other oil-related world events, like the Iraq crisis and the Gulf Hurricane, has made the oil price rise to around 140 Dollars per barrel in July 2008. There are also environmental concerns about Global warming. Even though it is still a subject for discussion, it is widely believed that the human contribution to the increase of CO_2 in the atmosphere is one of the main causes of temperature rise. Governments are about to introduce CO_2 Emission rights and open an emission trade to stimulate the reduction of CO_2 emission and, for instance, underground CO_2 storage.

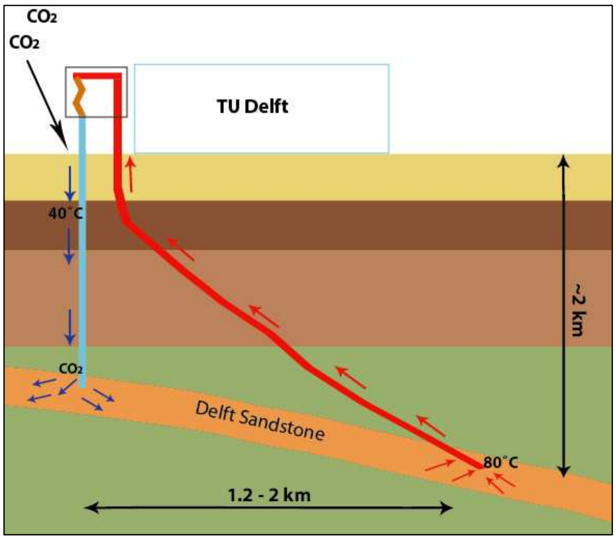

Figure 1: Schematic plan of the DAP geothermal doublet

These conditions motivated Students of Delft University, Department of Applied Earth Sciences to launch a project that combines the production of geo-energy and CO_2 storage. The project is called "Delft Aardwarmte Project" (DAP) and the goal is CO_2 neutral heating by using geothermal energy. In order to achieve this sustainable and innovative solutions are required and created by combining research and education. Composite drilling and the injection of CO_2 are studied and will be applied in the project. Innovative composite drilling is expected to meet the requirements of the urban environment. The light weight will make it possible to use little space while drilling the wells. The other advantage is that it should be better resistant to the corrosive geothermal fluids and less expensive compared to regular steel tubing.

Within the "Delft Aardwarmte Project" warm water is planned to be produced through a geothermal doublet: one well to produce the warm water and an injector well to send back the cold water into the reservoir. The warm water is going to be recovered from the Delft Sandstone Formation which is present in the underground of the TU Delft campus. In a pre-study within DAP, using the data of nine wells drilled for oil and gas exploration, is shown that an anticline is present about 1.6 to 2 km below the university grounds. The Delft Sandstone is in general a highly permeable sandstone formation and has to produce about 150 m^3 of water per hour. The temperature at depth is about 80°C which is too low to for the existing heating grid on the campus, but enough to be used for new and renovated facilities.

The water is going to be reinjected to meet the environmental requirements of brine disposal but also serves to remain reservoir pressure and increase energy extraction efficiency, the setup is shown in Figure 1.

The determination of the inter-well spacing is important for the feasibility and the optimization of the extraction of geothermal energy. It has strong influence on the well costs, the life span of the project, but also on the strategy of future geothermal wells by the same or different owners.

At surface, the distance between the wells is just 2 meters but at reservoir depth the distance is 1 to 2 kilometers. The distance at reservoir depth is determined by the permeability of the sand layer, the flow rate and the reheating by the formation of the injected cold water resulting in a thermal breakthrough time, e.g. the point in time where the production temperature starts declining caused by the injection of cold water. The differences between the properties of the produced and the injected water can cause certain flow mechanisms that may lead to a different breakthrough time.

This paper describes the mechanisms occurring during injection and the prediction of the thermal breakthrough studied using a reservoir simulation model developed for the "Delft Aardwarmte Project" field properties.

Nomenclature

K	Permeability	mD
Φ	Porosity	-
r_{well}	Well Radius	m
B	Thickness	m
W	Flow rate	m^3/hour
K	Thermal conductivity	W/(m·K)
T	Temperature	K or °C
U	Darcy velocity	m/s
V	Velocity	m/s
G	Gravity	m/s^2
C	Specific heat capacity	J/(kg·K)
µ	Viscosity	Pa·s
P	Density	kg/m^3
T	Time	s
R_T	Thermal Retardation Factor	-

Subscripts

I	Injected
0	Initial / virgin
W	Water
R	Rock
Eq	Equivalent

2. Geology

2.1. Geological setting

Knowledge of the geology is of great importance for successful implementation of the geothermal system. The subsurface of the TU Delft region is sited in the West Netherlands Basin, which has been an area of oil production since 1954. (De Jager et al, 1996) The basin existed from the Late Jurassic to the Early Cretaceous and opened in a series of NW-SE trending rift basins forming half-graben structures. While being formed these rifts were filled with fluvial sediments. (den Hartog Jager, 1996). During the Late Cretaceous compression occurred leading to the reactivation of the earlier faults. This resulted in the formation of complex inversion structures and NNW-SSE fault structures. (De Jager, 2007)

For geothermal heat purposes there are two intervals of interest in Zuid-Holland: the Lower Triassic and the Lower Cretaceous sandstones (Lokhorst & Wong, 2007). Research within DAP looked at the Lower Cretaceous sandstones. There are three formations which are potentially interesting: the Berkel sandstone, the Rijswijk sandstone and the Delft sandstone. The shallowest of the three is the Berkel sandstone but this one is not interesting because of the low temperature. The Rijswijk sandstone is formed during coastal transgression sand and has good lateral continuity. The Delft Sandstone is a stacked distributary-channel deposit with massive sandstone sequences (Van Adrichem Boogaerdt & Kouwe, 1993).

The Delft Sandstone Formation is chosen to be the target zone for the geothermal system of DAP because it is situated below the Rijswijk sandstone, which means higher aquifer temperature and because of the potentially high reservoir qualities of the Delft sandstone. In an ongoing study within DAP the target horizon, the Delft sandstone, was interpreted with the use of seismic data provided by the NAM. An anticlinal structure was found. Data from 45 wells from the surrounding of Delft supported the interpretation (Smits, 2008).

2.2. Temperature Gradient

In the Netherlands the geothermal gradient is about 3ºC per 100 meters. For verification of this gradient a TNO study (Simmelink et al, 2007) was performed for the Den Haag Geothermal project resulting in a specific temperature gradient. The reservoir temperature for the DAP target zone is estimated using this Den Haag relation (Smits, 2008). If we look at this target zone for DAP we see that the Delft Sandstone goes to a depth of around 2100 to 2500 meters. This corresponds to an in-situ temperature of 75ºC to 80 ºC. Appendix B shows a depth map of the top DS converted with the Den Haag relation to a temperature map.

2.3. Reservoir Properties

Unfortunately the wells drilled in the TU Delft area do not provide enough information about the reservoir properties of the Delft Sandstone. To make a good prediction of the porosity and the permeability data from an analogue field is used. This field is the Moerkapelle field located about 15 kilometers north-east of the TU Delft area. The Moerkapelle field is a heavy oil field with the Delft Sandstone at a depth of about 800-1000 meter. Petrophysical analysis of the logs from the Moerkappelle wells provided average properties for the Delft Sandstone:

Average porosity:	0.18
Average Permeability:	495 mD
Average Thickness:	50 m

3. Geothermal system

3.1. Factors influencing the doublet spacing

A doublet system is the proper method for low-enthalpy geothermal heat mining, such as the "Delft Aardwarmte Project". The underground distance between the producer- and the injector well, the doublet spacing, for economical heat mining is influenced by certain reservoir related factors: Thickness of layer (the net thickness of good quality reservoir), porosity and permeability. They influence the breakthrough time for geothermal systems and are therefore important for determination of the optimal doublet spacing (Walter, 1994).

The amount of volume produced per time, the flow rate, is the next important factor for the determination of the optimal well spacing. The minimal flow rate needed for an economical system depends on the requirements at the surface (heat exchange unit) while the maximum flow rate is determined by the reservoir in the underground.

Fluid and Rock thermal properties will determine the amount of heat transported to the injected water and the cooling of the reservoir interval between the wells. Subsequently, the temperature dependant fluid and rock properties may cause the occurrence of certain flow mechanisms in the reservoir.

Heterogeneity within the reservoir is a very important aspect for successful breakthrough time prediction and optimal well spacing. If there is a high permeable channel present between the two wells, flow will be mainly through this channel. This will result in a much shorter time for the injector water to reach the producer well and, because of less contact of cold water with the warm reservoir, temperature will decline more rapidly.

There are two other factors that may be important for the breakthrough time prediction for the geothermal well spacing. These are pore space clogging and aquifer influx. For each a short description is given but they are not further discussed in this study.

Mechanical or chemical clogging of the pore space is are other phenomenon that can influence the behavior of the geothermal reservoir is pore space clogging. Due to the high production rates mechanical clogging can occur, especially around the well bores where fluid velocity are high the original reservoir structure can be wrecked and a combination of small and large particles can be drained towards the well clogging the pore space. The pore space of reservoir sandstones can also be clogged by precipitation of minerals such as anhydrite. Two geothermal systems in the North German sedimentary basin are, for instance, known cases where a secondary anhydrite cementation drastically reduced the originally high permeability (Wagner et al, 2005).

A natural flow or an aquifer influx may influence the induced flow between the producer and the injector well. For now in the DAP case it assumed that this can be neglected.

3.2. DAP conditions

For the DAP case the injector well is going to be drilled vertically to the top of the anticline in the Delft Sandstone Formation. The producer is drilled from the same location at surface to a position that is about 2 km away from the vertical well at reservoir depth. The producer is drilled to a location further down dip towards a deeper part of the reservoir because of the higher temperature that is present there. The maximum drilling deviation is 60 degrees from vertical. The desired production rate is 150 m^3 per day and is reduced during the summer by 50%. The system produces from a certain depth that the water temperature is about 80°C. The produced water is cooled down to a temperature of 40°C and then re-injected. The minimal production temperature to ensure the systems efficiency is 70 degrees Celsius. When the water is flowing towards the surface it will also cool on its way up. The temperature loss is estimated at 2 degrees Celsius after the well is being warmed up (steady state).

3.3. Aquifer Fluid

The aquifer fluid is a brine with high salinity. From the literature some chemical compositions of water from similar aquifers are available (Appendix A). In this study it is assumed as a 8 wt% NaCl aqueous solution with corresponding properties.

4. Fluid flow and Heat Transfer

When cold water is injected in a reservoir with higher temperature the fluid will flow along the pressure gradient and heat transfer from the rock to the fluid will occur. The energy transfer consists of convection forced by injection (advection) and conduction and will lead to a thermal front moving away from the injector.

The propagation of thermal front for single-phase flow in homogeneous porous media was first studied by Bodvarsson (1972). By neglecting thermal conduction as insignificant relative to convection he developed analytic solutions to the governing equations and revealed two important points: the temperature front lags the fluid front by a constant related to the heat capacities of rock and water and the there is an abrupt change from the initial temperature to the injection temperature. Woods and Fitzgerald (1993) concluded that for homogeneous media thermal conductivity was indeed negligible for a wide range of circumstances.

The effect of thermal conductivity for flow in heterogeneous media was investigated by Shook (2001) who concluded that neglecting the conduction is a good assumption for heterogeneous, non fractured media. In fractured media the conduction of heat in the direction of the face of the fracture will play a more important role.

Stopa and Wojnarowski (2005) obtained an analytical solution for rock-fluid properties as a function of temperature. They found a temperature-dependent propagation speed of the thermal front.

4.1. Thermal retardation factor

If we assume local thermodynamic equilibrium between rock and fluid because rock grains are sufficiently small and fluid velocities are low, the conservation of energy and mass equation for a single phase fluid can be written in this manner:

$$\varphi\frac{\partial\rho_w}{\partial t}+\vec{\nabla}\cdot(\rho_w\vec{u}_w)=0 \tag{1}$$

$$\underbrace{\frac{\partial\left(\rho_{eq}C_{eq}T\right)}{\partial t}}_{\text{Temperature Change}}+\underbrace{\vec{\nabla}\cdot(\rho_w\vec{u}_wC_wT)}_{\text{Convection}}=\underbrace{\vec{\nabla}\cdot(K_{eq}\vec{\nabla}T)}_{\text{Conduction}} \tag{2}$$

where

$$\rho_{eq}C_{eq}=\varphi\rho_wC_w+(1-\varphi)\rho_rC_r \tag{3}$$

And the combined conductivity is a function of rock and thermal conductivities

$$K_{eq}=K(K_r,\varphi,K_w) \tag{4}$$

If we assume incompressible rock and constant thermal properties of both rock and fluid and neglect conduction as second order effect we can combine equations 1 and 2 to get an equation that describes the velocity of the thermal front in porous media (Bodvarsson, 1972; Shook, 2001).

$$\frac{\partial T}{\partial t}+\frac{u_w}{\varphi}\left(\frac{\varphi\rho_w C_w}{(1-\varphi)\rho_r C_r+\varphi\rho_w C_w}\right)\vec{\nabla}T=0 \tag{5}$$

The following equation describes the velocity of the thermal front is retarded relative to the fluid velocity :

$$\frac{v_T}{u_w/\varphi}=\frac{v_T}{v_w}=\left(\frac{\varphi\rho_w C_w}{(1-\varphi)\rho_r C_r+\varphi\rho_w C_w}\right)=R_T<1 \tag{6}$$

Here R_T is the thermal retardation factor. So the thermal front velocity is the fluid velocity times the factor R_T. However, strong assumptions have been made. Especially the differences in temperature dependant properties between the warm produced and cold injected water may cause buoyancy flow. This is described in the next chapter.

5. Bouyancy Flow

The density of the water in the DAP reservoir is temperature dependant. Density variations can initiate flow even in a fluid at rest. In the underground, variations in density can occur from naturally occurring salts, subsurface temperature changes, or migrating pollution. In the DAP case the density-driven flow mechanism for the warm aquifer water (T=80°C, ρ=1048) and cold re-injected water (T=40°C, ρ=1032) which flows downwards an inclined layer may cause underruning of the injected water, leading to larger errors in temperature prediction. This is illustrated by Figure 2.

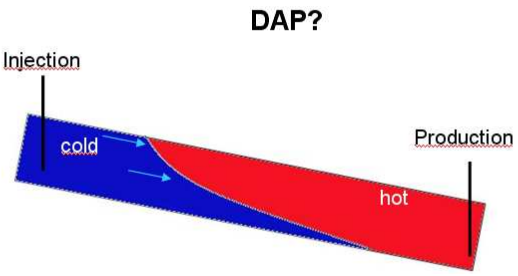

Figure 2: Illustration of the possible flow mechanism for the cold and warm water.

5.1. Darcy's Law and non constant density

This problem for time dependent buoyancy flow in porous media and is analogue to the Elder problem (appendix B) which can be analyzed using COMSOL.
Darcy's law for petroleum Engineers in 2d for x and z (downward direction) components reads (Bruining, 2006):

$$u_x=-\frac{k}{\mu}\frac{\partial p}{\partial x}$$

$$u_z=-\frac{k}{\mu}\left(\frac{\partial p}{\partial z}-\rho g\right) \tag{7}$$

For incompressible media:

$$\nabla \cdot \vec{u} = 0$$

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} = 0 \quad (8)$$

For non constant density an extra term remains present for density driven flow:

$$-\frac{\partial}{\partial x}\left(\frac{k}{\mu}\frac{\partial p}{\partial x}\right) - \frac{\partial}{\partial z}\left(\frac{k}{\mu}\frac{\partial p}{\partial z}\right) + g\frac{\partial}{\partial z}\left(\frac{k\rho}{\mu}\right) = 0 \quad (9)$$

With density and viscosity as a function of temperature the approximation of the properties for intermediate temperatures by linear interpolation becomes:

$$\rho(T) = \rho_0 + \Delta\rho \frac{(T_0 - T)}{(T_0 - T_i)} \quad (10)$$

$$\mu(T) = \mu_0 + \Delta\mu \frac{(T_0 - T)}{(T_0 - T_i)} \quad (11)$$

The density difference will cause the cold water with higher density to flow down the warmer water. On the other side the viscosity difference will act as an adverse factor on this effect. When colder water 'underruns' having an higher viscosity the pressure gradient changes. This causes the water velocity in the upper section to increase in relation to the 'underrunning' water. So the viscosity difference will reduce (or even counterbalance) the effect of the density difference.

To analyze this mechanism for the DAP case we can combine the equations (1-4) already described in chapter 5 with equations (6-9) and solve them using a numerical simulation model in COMSOL Multiphysics that uses the Finite Element Method.

5.2. Model description

This model examines the buoyancy flow problem for the DAP case through a 2-way coupling of two application modes from the Earth Science Module: Darcy's Law and Convection and Conduction in Porous Media. In essence the equations (1-4) and (6-9) have been applied in 2D rectangular region representing a vertical cross section model of the homogeneous inclined reservoir layer. It is not needed to neglect the equations for conduction because it can be easily solved with COMSOL and even improves convergence in the numerical calculations.

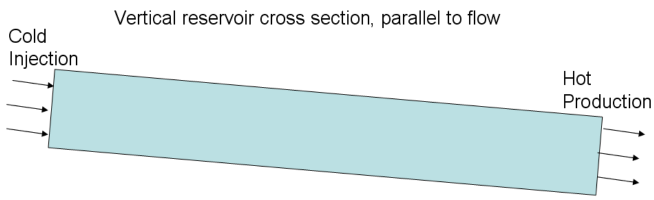

Figure 3: Schematic illustration of the model

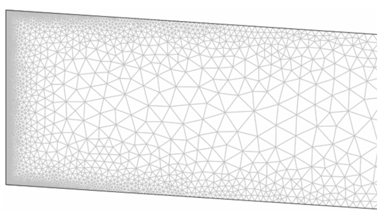

Figure 4: Snapshot of the mesh

Geometry and Mesh

In this model a vertical cross section of water-saturated porous media is representing the reservoir. The thickness is 70 meters, the dip is 8° and horizontal length 2000 meters (Figure 5: **Geometry of the model**).

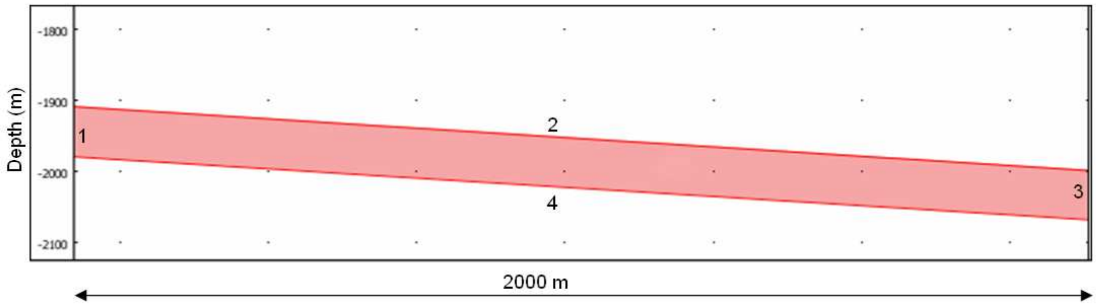

Figure 5: Geometry of the model

Initial and boundary conditions.

The water is initially stationary with a hydrostatic pressure distribution, gravity in negative vertical direction, and with virgin aquifer temperature T0. At edge 1 (Figure 5) the pressure is altered with 2,5E5 Pa on top of the hydrostatic pressure and at edge 3 the pressure is lowered with 2,5E5 Pa to create a pressure gradient and fluid velocity representative to the DAP case (minimum Darcy velocity *u* between wells is around 10^{-6} and $5 \cdot 10^{-7}$ m/s). For the heat transfer the boundary condition at edge 1 is the injection temperature Ti. There is no flow and a zero temperature gradient across edges 2 and 4. The period of interest is 20 years.

Data

The model works with the following data:

Parameter	Name	Value
k	Permeability	495 mD
φ	Porosity	0.18
K_w	Water thermal conductivity (EngineeringToolBox, 2008)	0.58 W/(m·K)
K_r	Rock thermal conductivity (EngineeringToolBox, 2008)	4.0 W/(m·K)
T_i	Injection Temperature	313 K = 70°C
T_0	Virgin Temperature	343 K = 40°C
g	Gravity	9.81 m/s^2
C_w	Water Specific heat capacity	4184 J/(kg·K)
C_r	Rock specific heat capacity (see Appendix A)	920 J/(kg·K)
μ_i	Viscosity at T=313 K (Kestin et al, 1981)	0.000726 Pa·s
μ_0	Viscosity at T=343 K (Kestin et al, 1981)	0.000472 Pa·s
ρ_i	Density at T=313 K (SaltInstitute, 2008)	1048 kg/m^3
ρ_0	Density at T=343 K (SaltInstitute, 2008)	1032 kg/m^3

Table 1

5.3. Model Results

The following results for the thermal front come from the COMSOL solution. Figure 6 gives the solutions for the thermal front interval for two different cases of permeability.

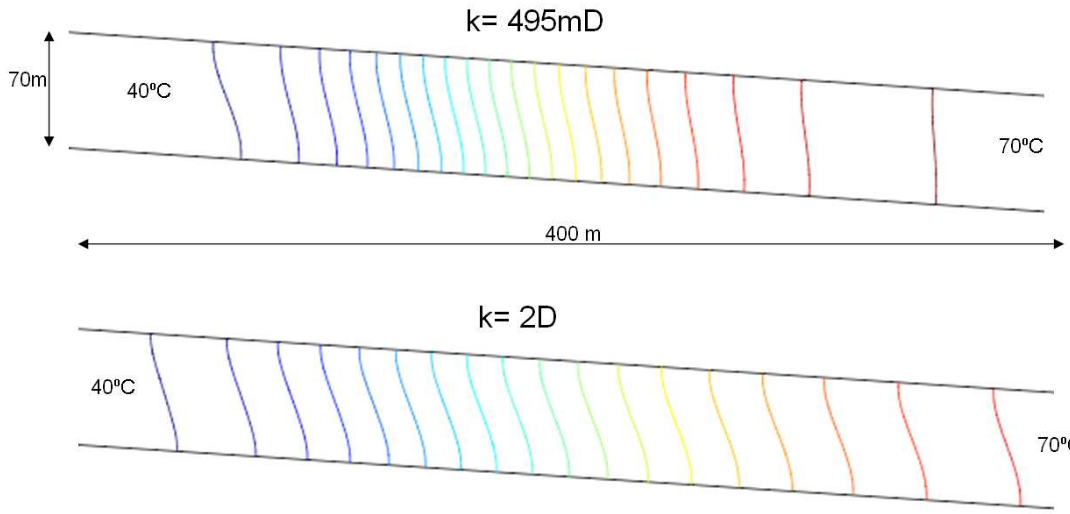

Figure 6: Snapshots of the thermal front interval solutions for a permeability of k=495mD and k=2 D. The coloured lines represent temperature and indirectly viscosity or density.

For the described model with permeability of 495 mD a tilted interface between cold and warm water is present and there is some underruning of cold injection water due to buoyancy flow. However, the angle of the interface is insignificant realizing the lateral distance is 2000 m with a layer thickness of 70 m. Also shown in Figure 6 is the same model but with a much higher permeability. The solution shows that higher permeability will increase the effect of buoyancy flow in terms of a flatter interface. But even with this 4 times higher permeability the angle of the thermal front is still insignificant to the extend of the reservoir. Therefore, it is not expected that the occurrence of this mechanism will give large errors in breakthrough time prediction.

In addition different values for the density difference (up to $\Delta\rho$ =100 kg/m^3) did not result in appreciable difference in the angle of the thermal front.

5.4. Layered System

In this paragraph the same problem as in section 5.3 will be described but now for a layered system. The next model shows the effect of permeability layering on buoyancy flow. Now the model of section 5.2 was rerun but now divided into two layers with a high permeable lower layer. The top half has a permeability of 495 mD, and the lower half 2 D. This model was also run with constant properties (density and viscosity). Figure 7 shows the results of these simulations. The temperature profile is shown, the darkest red represents a temperature of 70°C and blue 40 °C. The simulation was run first with constant fluid properties (no buoyancy flow) and then for density and viscosity dependant on temperature. The results, showed in Figure 7, show a very similar temperature profile and little effect of buoyancy flow. Thus, gravity effects are almost completely offset by viscous forces and it is not expected that buoyancy flow will give a large error for flow predictions in case of a high permeable lower layer.

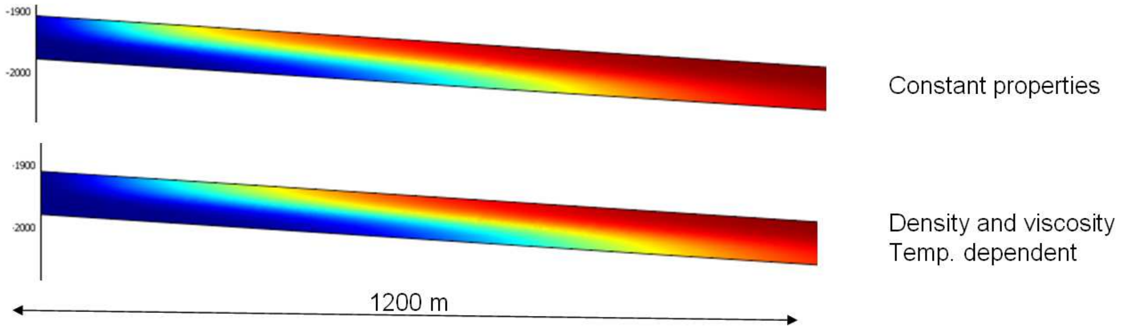

Figure 7: Thermal front simulation of cold water injection for a layered system.

6. Predicting Thermal Breakthrough

The prediction of thermal breakthrough for the DAP geothermal project was studied using a model for a two-dimensional, areal, horizontal model in COMSOL Multiphysics.

6.1. Model description

An injection and a producer well were placed in an domain of 8000 m x 6000 m, visible in Figure 8 where I is the injector well and P the producer well. The boundary's of the domain where chosen such that it can be assumed that they are far away enough from the wells to remain at hydrostatic pressure and virgin reservoir temperature during the time of interest. Both wells have a well radius r_{well} of 0.1 meters and near the wells a fine mesh was defined (Figure 8). Equations (1-4) and (6-9) were again applied for this model.

The model was run for different values of the inter well spacing D, varied between 800 and 2000 m.

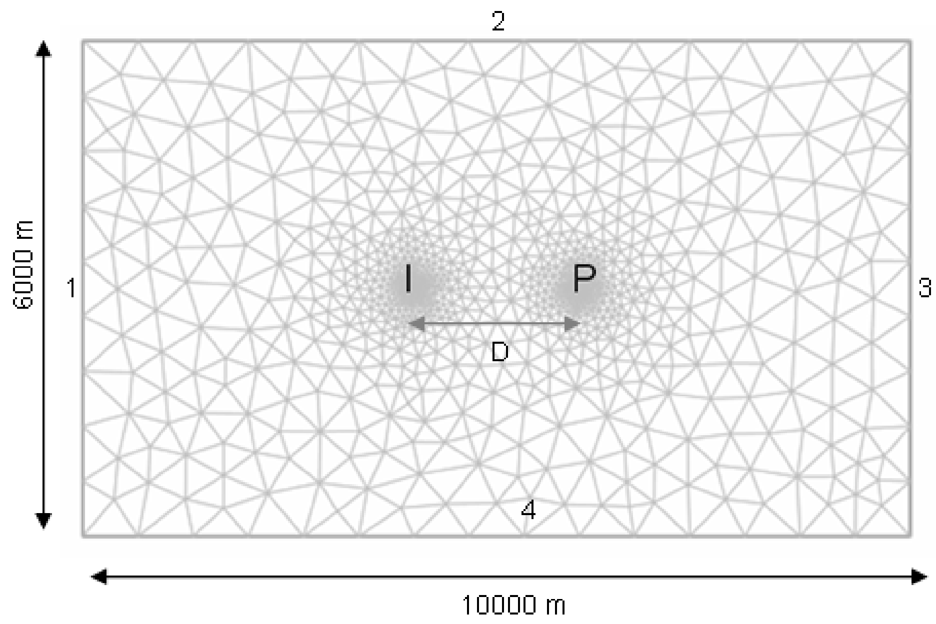

Figure 8: Geometry and mesh of the 2d horizontal model

Initial and boundary conditions

The reservoir is initially at hydrostatic pressure for a depth of 2000 m: p=ρ·g·h. At the model boundaries 1-4 (in Figure 8) the pressure is remained hydrostatic and the temperature equal tot the virgin temperature of 80°C. At the two-dimensional boundaries for the injection *I* well the Inward flux is defined as

$-W/(2\cdot\pi\cdot r_{well}\cdot b)$ and for the production well *P:* $W/(2\cdot\pi\cdot r_{well}\cdot b)$. The temperature at injector *I* is 40°C. Fluid density and viscosity chosen are constant and for all temperature dependant properties intermediate constant values (between the minimum and maximum temperature) are used.

Data

The model works with the following data:

Parameter	Name	Value
k	Permeability	495 mD
φ	Porosity	0.18
r_{well}	Well Radius	0.1 m
b	Thickness	50 m
W	Flow rate	150 m^3/hour
K_w	Water thermal conductivity (EngineeringToolBox, 2008)	0.58 W/(m·K)
K_r	Rock thermal conductivity (EngineeringToolBox, 2008)	4.0 W/(m·K)
T_i	Injection Temperature	313 K = 40°C
T_0	Virgin Temperature	353 K = 80°C
g	Gravity	9.81 m/s^2
C_w	Water Specific heat capacity 8 wt% NaCl solution (EngineeringToolBox, 2008)	3800 J/(kg·K)
C_r	Rock specific heat capacity (see Appendix A)	875 J/(kg·K)
μ	Viscosity	0.0006 Pa·s
ρ_r	Matrix Density	2300 kg/m^3
ρ_f	Water Density	1037 kg/m^3

Table 2

6.2. Results

Figure 10 shows the temperature near the production well versus time curves for different values of the doublet spacing *D.* When the curve starts declining under the initial 80°C value thermal breakthrough occurs. The current planned doublet spacing (D=2000 m) will not show temperature change until about 44 years. This exceeds the life-span of the wells which is about 30-40 years. If in the summer the production rate of the system will be further reduced the breakthrough time will be even higher. Therefore the planned 2000 m doublet spacing should be more than enough.

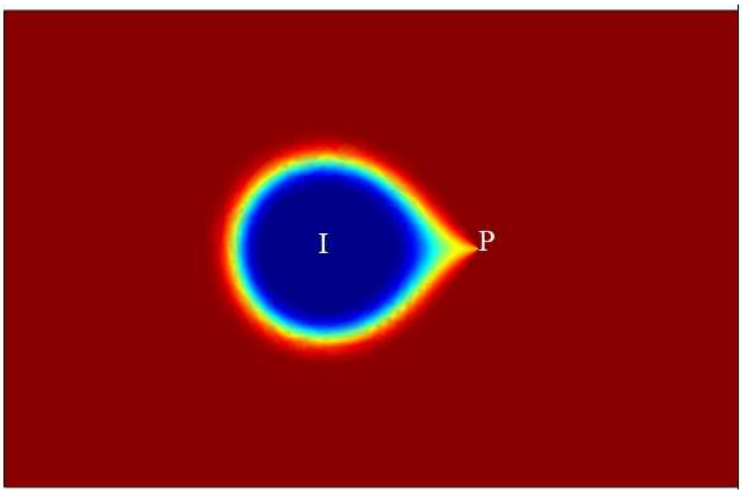

Figure 9: Example of typical temperature profile for cold water breakthrough in the 2d horizontal homogeneous model with temperature independent properties.

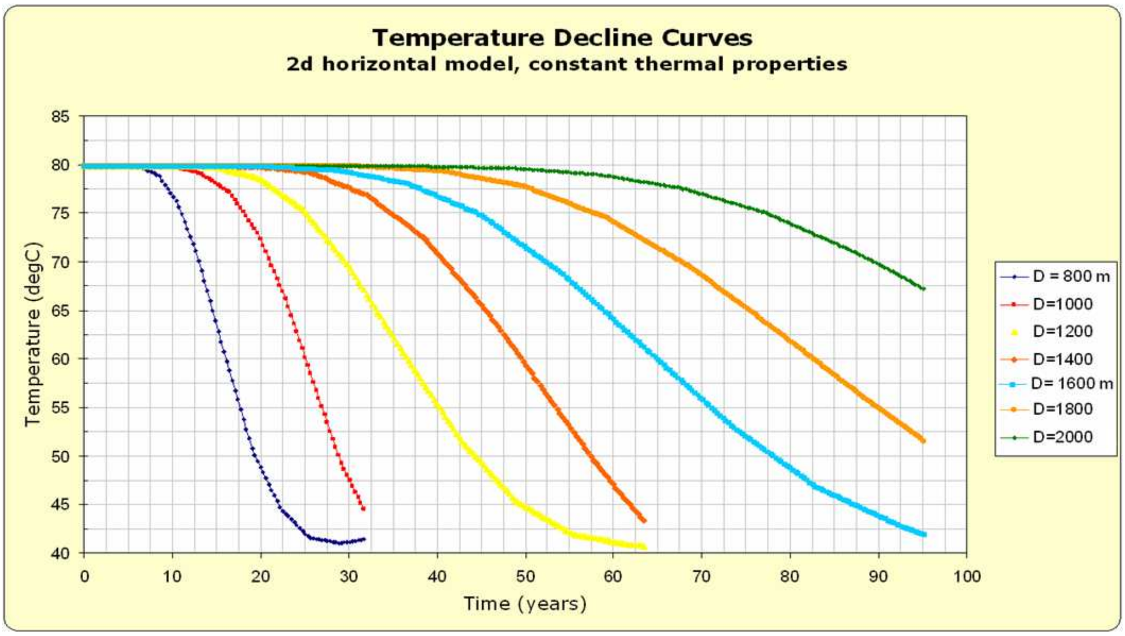

Figure 10: Temperature Decline Curves for the 2d horizontal model with temperature independent properties for different values of the inter-well spacing *D*.

Post-breakthrough temperature

Before only the thermal breakthrough was discussed but if looking at the decline curves in Figure 10 we see that after thermal breakthrough the temperature remains above the minimum temperature (for DAP: 70°C) for a certain period. The temperature plotted in Figure 10 from the COMSOL model is not the production temperature but the temperature in the model at one side of the production well as illustrated in Figure 11. This means that the production temperature after thermal breakthrough is somewhat higher than showed in the curves and therefore it is expected that the system can remain efficient for more years after thermal breakthrough.

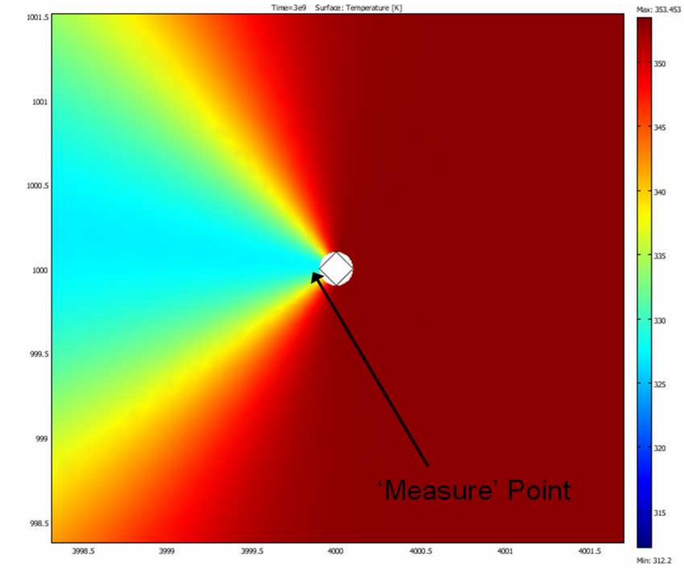

Figure 11: 'Measure' Point in the model at the production well. The cold water (light blue colour) broke through from the left in this temperature profile.

Temperature decline curves vs. reservoir thickness

The model was rerun for different values for the reservoir thickness *b* and the results are shown in Figure 12.

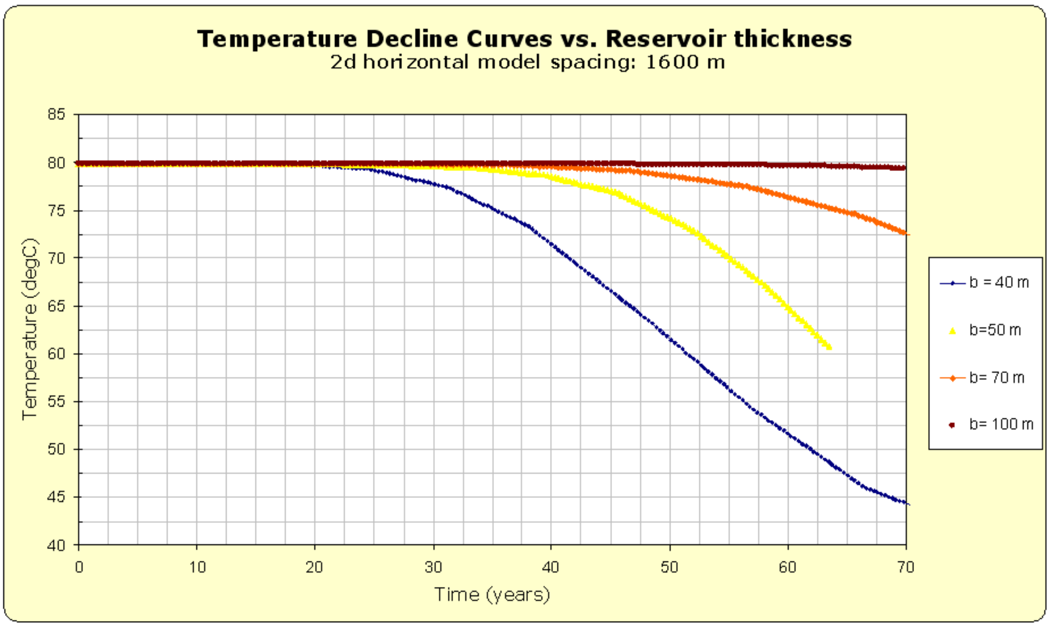

Figure 12: Temperature decline curves vs. reservoir thickness for a spacing of 1600 m.

Temperature decline curves vs. porosity

Figure 13: **Temperature curves for different values for porosity.** shows the sensitivity of porosity on the results of the numerical simulations for the model with a spacing D of 1600 m.

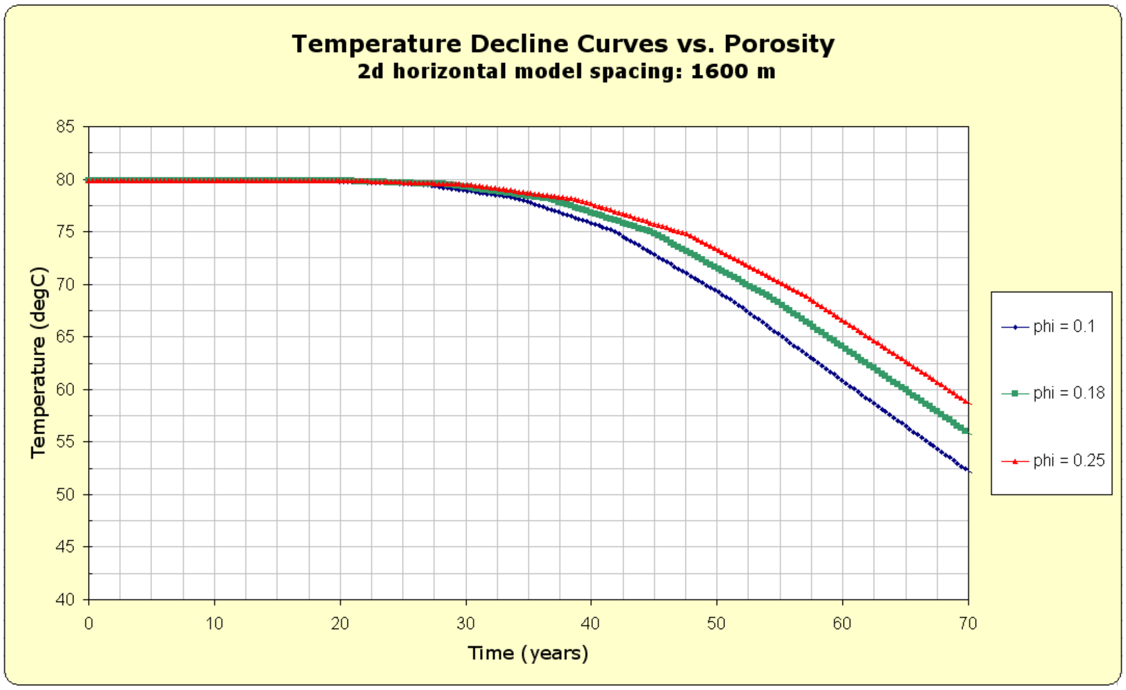

Figure 13: Temperature curves for different values for porosity.

Temperature dependant properties

Next the influence of temperature dependant properties of rock and fluid on the breakthrough time prediction was analyzed. The temperature dependence of the fluid properties was already discussed in section 5. The specific heat of rock also depends on temperature and usually increases with temperature. The model from 6.1 was changed such that the parameters viscosity and heat capacity are temperature dependent. Fluid (8 wt% NaCl) specific heat was defined constant because of lack of available data. Thermal conductivity was remained constant, because that would not change anything significantly. The temperature dependent expressions are shown in Table 3.

Parameter	Name	Value/Expression
T_i	Injection Temperature	313 K = 40°C
T_0	Virgin Temperature	353 K = 80°C
C_w	Water Specific heat capacity 8 wt% NaCl solution (EngineeringToolBox, 2008)	3800 J/(kg·K)
C_r	Rock specific heat capacity (Apendix A, Figure A-1: Somerton curve)	$900-40\cdot(T_0-T)/(T_0-Ti)$ J/(kg·K)
μ	Viscosity 8 wt% NaCl solution (Kestin et al, 1981)	$0.000472+0.000254\cdot(T_0-T)/(T_0-T_i)$ Pa·s

Table 3

Figure 14 compares the temperature decline curves for the two models for a well spacing of 1800 m. The result is an as good as similar thermal breakthrough time but a significant difference is the post-breakthrough temperature. In fact, the post-breakthrough temperature for this temperature dependant model seems to be more favorable for the geothermal heat mining.

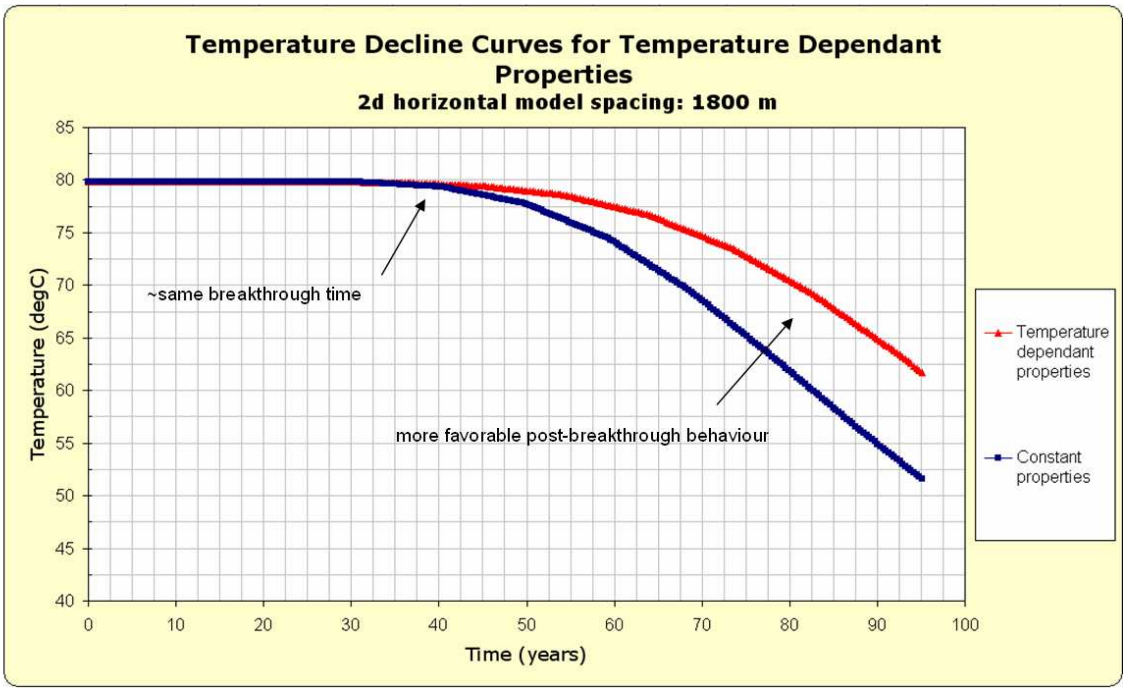

Figure 14: Comparison between the use of constant or temperature dependent properties

Optimal Well Spacing

Regarding the temperature decline curves resulting in a breakthrough time and a post-breakthrough temperature curve a more optimal doublet spacing would be between 1500-1600 meters. Then the breakthrough time will be near the end of the lifetime of the wells and if this is earlier the post breakthrough temperature curves show that the system can remain efficient for another period (Figure 12 and Figure 14). Uncertainties of reservoir thickness seem to have to largest impact on the calculations for the temperature curves (Figure 12) and the model is less sensitive to porosity (Figure 13).

6.3. Three-dimensional Model

For the combination of the temperature dependant properties and the gravity influence on the anticlinal structure a three-dimensional reservoir simulation model was initialized in COMSOL. However more work and tuning are needed to make this three-dimensional model in COMSOL work with the conservative form of the *Convection and Conduction in Porous Media* application and temperature dependant properties.

Model description

Therefore, the model is completed with constant fluid and rock properties. The reservoir is defined as a 50 m thick rectangular block of 6000 m x 10000 m under an angle of 8 degrees. Two wells with a spacing of 2000 m are crossing the reservoir vertically. Production and injection is again 150 m^3/hour. Initial temperature is in accordance with the temperature gradient and initial pressure is hydrostatic. At all the vertical faces the boundary values for pressure and temperature is remained constant (initial values). At the horizontal faces there is a zero temperature gradient condition.

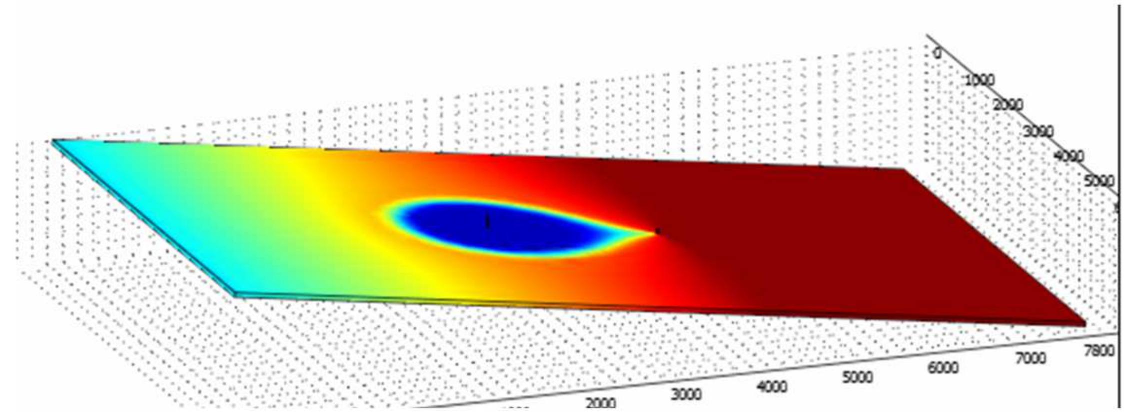

Figure 15: Snapshot of the 3d model. The colours represent the temperature and the temperature gradient is visible.

Results

The temperature decline curve shows a declining temperature from the start due to production along the temperature gradient. This effect is again caused by the point of measurement in the model (Figure 11). Warmer water (according to the temperature gradient) flows into the well from the other side counterbalancing the production temperature. Breakthrough time and post-breakthrough behavior show the same trend as the results for the 2d horizontal model.

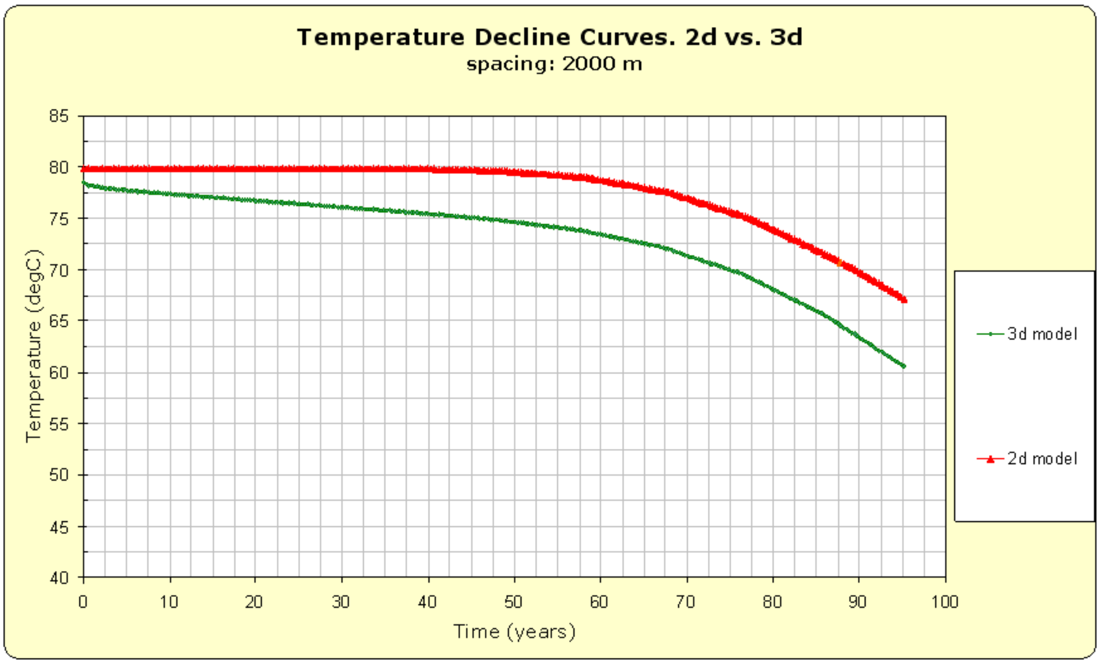

Figure 16: Temperature decline curves for 2d horizontal model and 3d model.

6.4. Heterogeneous Case

The final case studied is for heterogeneity in the reservoir. Heterogeneity is a very important aspect in reservoir modeling and will also play an important role for the prediction of flow in the geothermal reservoir. A high permeability zone between the injector and producer well may act as a ‘highway’ for the cold water and breakthrough will be much earlier than expected. On the other hand a permeability barrier between the wells will cause a fail in pressure support to the producer well and the required flow rate may not be reached. In this stage of the DAP project a study is being performed to get more insight in the heterogeneities is performed. It is assumed that the sands between the planned wells are well connected and the study shows permeability ranging from 54 mD to 700 mD (Smits, 2008). To see the effect of heterogeneity on the fluid flow and heat transfer a random permeability field (Figure 17) was generated using a uniform distribution between 50 mD and 1 D and added to model 6.1.

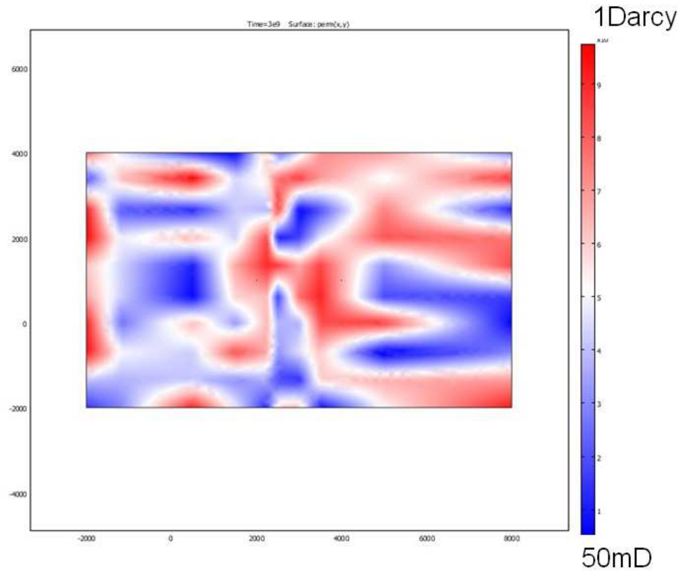

Figure 17: Permeability field

Note that the spatial distribution in this permeability model is unrealistic. Therefore only the effect of the permeability differences can be studied and not the effect on breakthrough or temperature production. As follow up a more realistic spatial distribution of the permeability using, for instance, the Monte Carlo method could be used.

In Figure 18 the result of the temperature profile at breakthrough of this heterogeneous model is shown. The colors represent temperatures (blue cold, red warm). As expected the temperature front also moves faster along the higher permeable regions lagging the fluid flow. In the figure the comparison is made between the use of constant viscosity and temperature dependant viscosity is visible. There is a slight difference. The temperature dependant case is more smooth and the region near the producer is less cold than for the constant viscosity. The viscosity difference between cold and warm water causes this. When cold water flows in to a higher permeable region the pressure gradient change because of the higher viscosity relative to the warm water. This causes more cold water to flow in less permeable regions. This is called viscous crossflow (Shook, 2001) and will retard the thermal breakthrough in case of heterogeneities.

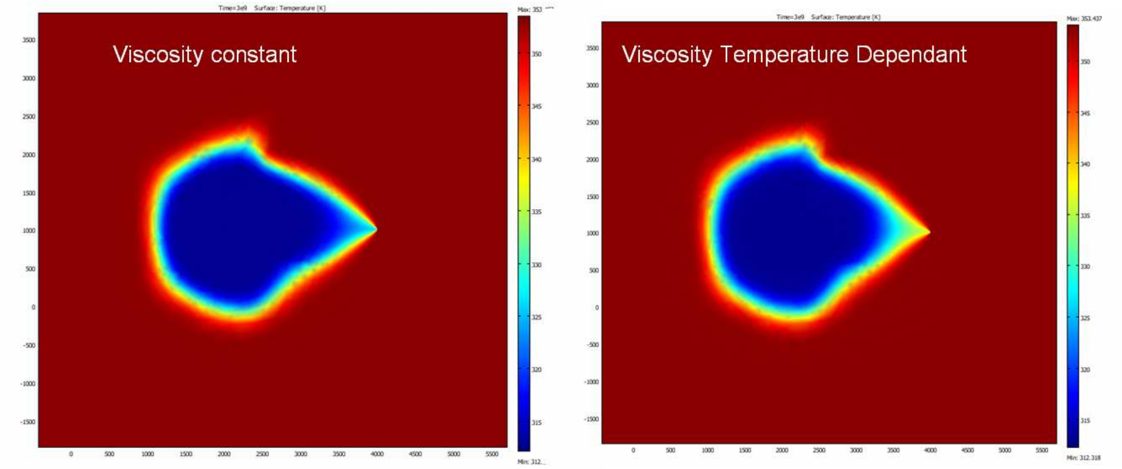

Figure 18: Comparison: use of constant viscosity or temperature dependant viscosity.

7. Conclusions

The Earth Science Module of the software program COMSOL Multiphysics made it possible to combine the equations for Darcy's law and heat conduction and convection in porous media to investigate buoyancy flow caused by injection of cold water in the reservoir. For the Delft Geothermal Project underrunning of the injected fluid due to density difference is not expected to give large errors in temperature prediction. Simulations show that the thermal front moves at

The current planned 2000 m spacing is more than enough. Calculations in an homogeneous reservoir model showed the first temperature change after 44 years of full production and a temperature higher than the minimum of 70°C for about 40 more years. Regarding the lifetime of the wells the optimal spacing between the wells would be between 1500 and 1600 meters.

The use of temperature dependent rock and fluid properties give the same thermal breakthrough time but a more favorable post-breakthrough behavior, in terms of a higher temperature.

Heterogeneous aspects are the key for successful temperature prediction as the thermal front movement follows the fluid flow with a certain lag. In Heterogeneous media viscous crossflow can occur retarding the thermal breakthrough. If there is more insight in the heterogeneity of the intended reservoir it is possible to study concrete values for the impact on these aspects on the temperature prediction.

8. Recommendations

To increase the accuracy of the temperature prediction it is recommended to investigate the heterogeneous aspects of the reservoir as well as the possibilities of geothermal clogging.

Furthermore, the COMSOL program would be a good option to use in a study on the occurring mechanisms in case of the injection of CO_2.

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Appendix A: Fluid an Rock Properties

Rock heat capacity versus temperature

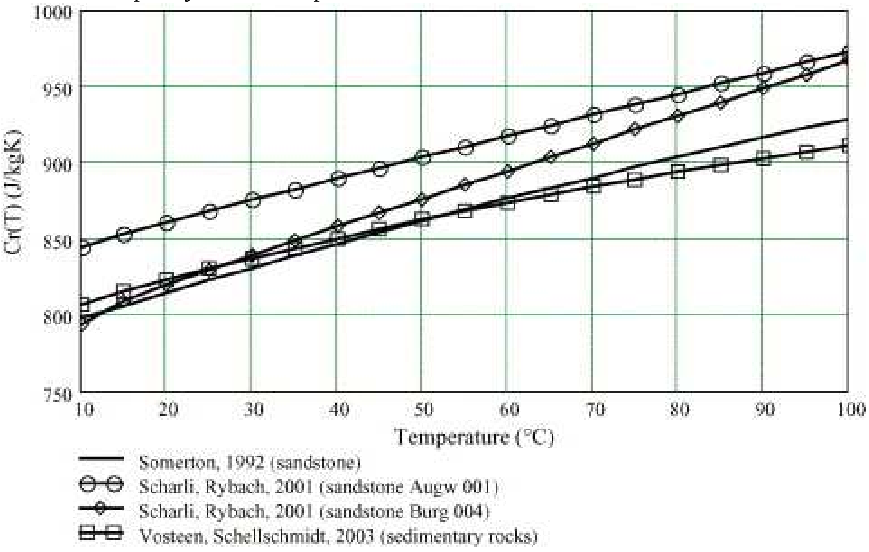


Figure A-1: Rock heat capacity versus temperature according to various authors (Stopa and Wojnarowski, 2006).

Aquifer Water

The following table shows the chemical compositions of aquifer water from the Delft Sandstone.

Parameter	De Lier (Zuurdeeg 1983) [g/l]	Onder-Krijt (Collins, 1975) [g/l]
Na^{+}	36,3	31,0
K^{+}	0,20	0,13
Ca^{2+}	3,6	7,0
Mg^{2+}	0,8	0,9
Sr^{2+}	0,58	0,2
Ba^{2+}	0,035	0,040
Fe^{2+}	0,033	-
Cl^{-}	55	62
SO_4^{2-}	0,15	0,28
H_3PO_4	0,02	-
H_4SiO_4	0,06	-
HCO_3	0,02	0,26
TDS	~97	~100

Analysis at TU Delft for the aquifer water of the Bleijswijk geothermal system showed a TDS of around 83 g/l, mainly Na^{+} and Ca^{-}. For calculations in this paper the aquifer water was simplified to an 8 weight % NaCl aqueous solution.

Appendix B: Target horizon and Temperature map

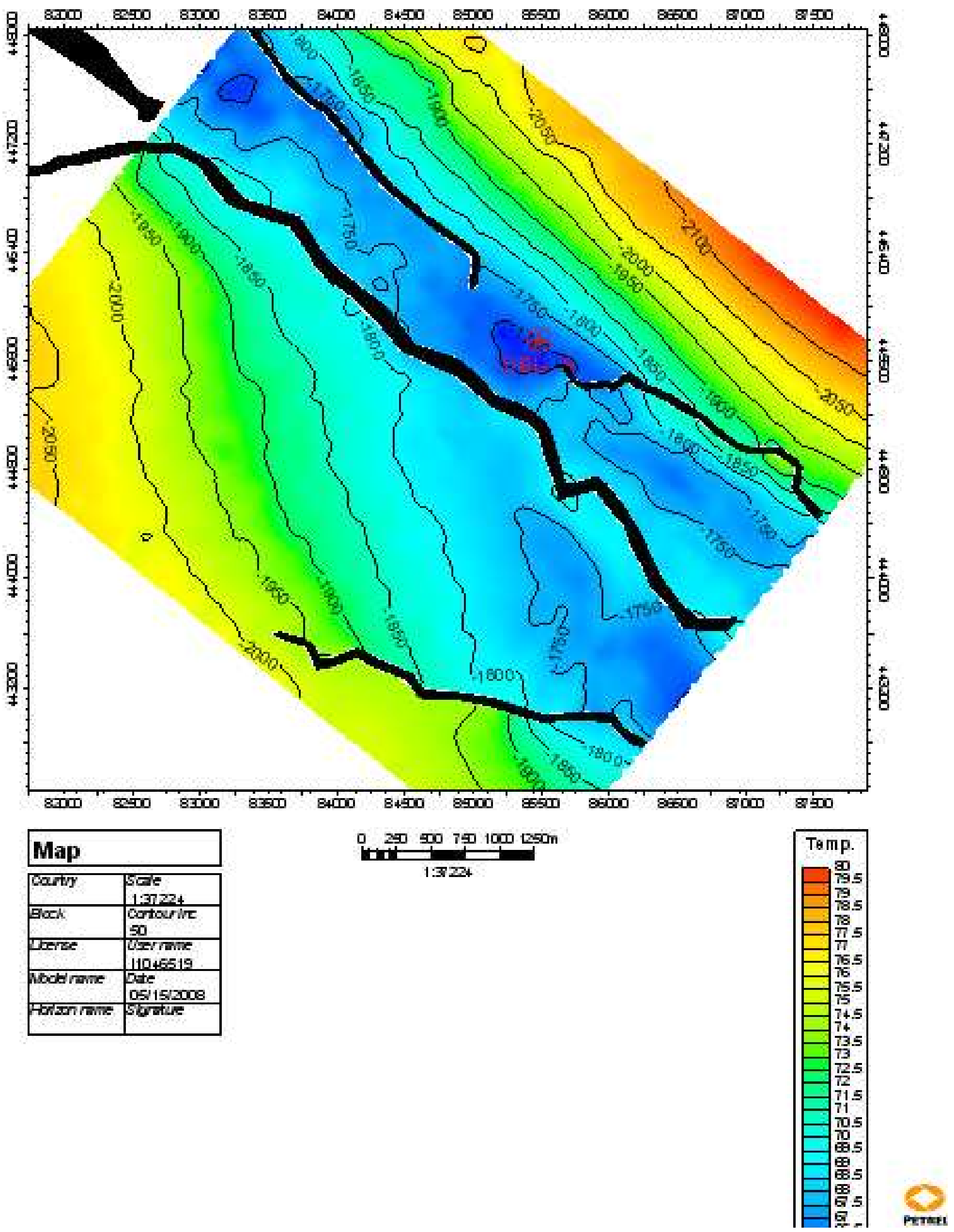
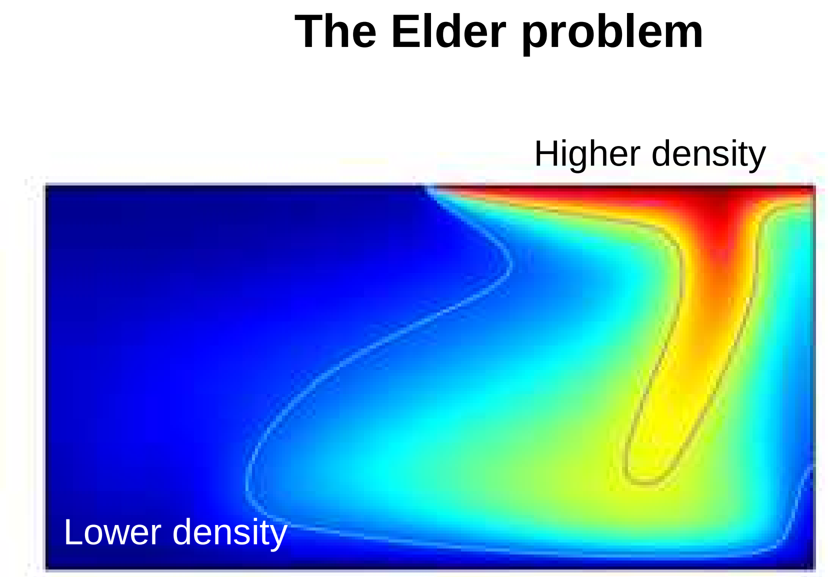


Figure Appendix B: Target horizon and Temperature Map. This map was created in Petrel by Peter Smits with the use of seismic- and well data provided by the NAM.

Appendix C: Analogy with the Elder problem.

The Elder problem is the benchmark problem for time-dependent buoyant flow in porous media. It follows a laboratory experiment to study thermal convection.



This figure shows the solution from COMSOL for the Elder problem after 15 years. The colours represent salt concentration. The water in the porous medium (this is a vertical cross section) is initially fresh. At the top right corner a certain salt concentration is present. This will lead to density-driven flow and diffusion of concentration in the porous medium. The model examines the Elder problem for concentrations through a 2-way coupling of two application modes from the Earth Science Module and is analogue to the model for buoyancy flow caused by temperature in the DAP case. The difference is that for the DAP case forced convection (advection) also occurs by the induced flow by the wells in the reservoir.

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