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20 June 2014 Birgit C. B. Biemans
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Picture on the front: Vertical fractures in the Shut-Ins rock, Missouri.
Taken from: aerialgeologist.blogspot.nl (James Berglund)
Abstract

This thesis looks into the possibility to produce geothermal energy in the Roer Valley Graben. The locations in this area are limited due to the low permeability of the deep Triassic layers. Fractures can enhance the heat production by increasing the effective permeability and decrease the pressure that is needed to produce the heat. However, fractures can also decrease the lifetime of a reservoir due to early breakthrough of the cold water.

The goal of this study is to explore the influence of fractures on geothermal heat production. Multiple 2D fracture patterns are modelled in a numerical finite element program and the fractures are represented as lower dimensional line elements.

The breakthrough time is strongly influenced by the position of the horizontal fractures. A smaller spacing between the fractures decreases the breakthrough time and the breakthrough time is increased if the orientation of the doublet is not in line with the fractures. The vertical fractures also influence the breakthrough if the fractures are connected to horizontal fractures.

The standard Advection-Diffusivity Equation (ADE), applied to an effective porous media, is fitted to the breakthrough curves of the numerical models by changing the apparent thermal dispersion. A different method, the Continuous Time Random Walk (CTRW) framework is also fitted to the numerical breakthrough curves. This framework, that is developed to describe solute transport, has five parameters that can be changed to create a fit. The global breakthrough curve is captured better by the CTRW, however the breakthrough is better described by the ADE. Both methods show similar results estimating the lifetime of the numerical model.

To determine when the ADE is able to describe the breakthrough curve of a certain fracture model, the area of influence of the fracture model is plotted against the error between the numerical experiment and the ADE. The area of influence describes the area that is influenced by the heat transport through the fractures. If the area of influence of a fracture pattern is small, the ADE has trouble describing the breakthrough curve correctly.

If the full width of the model is not covered by the area of influence, two cold fronts evolve, one through the fractures and one through the matrix. If the cold front of the
matrix would arrive at the outlet before the cold fluid through the fractures has cooled down the outlet, the breakthrough curve could not be described by the ADE.

If the fractures are placed in each other’s area of influence the cold injected fluid can travel further because it is less retarded by the matrix, creating an even earlier breakthrough. This effect is only visible if the area of influence of the fractures does not cover the full width of the reservoir.

To find a fit between the numerical results and the ADE, the thermal dispersion is adjusted to find the apparent thermal dispersion. I found that the area of influence also influences the apparent thermal dispersion. A negative relation could be constructed between the two parameters.

The discussion about thermal dispersion and its dependency on Peclet is also addressed in this thesis. Different relations between Peclet and the apparent thermal dispersion are studied and the relations varied from a linear relation to a power law relation. I found that the three regimes that [Detwiler et al. (2000)] constructed for solute longitudinal dispersion can also be constructed for the apparent thermal dispersion. For values of $\text{Pe}<1$, the apparent thermal dispersion has a very small negative to zero relation with $\text{Pe}$. For intermediate values of $\text{Pe}$ ($1<\text{Pe}<10$) Peclet is linearly related to the apparent thermal dispersion and for larger values of Peclet a power law relation can be constructed. The power law and the additional thermal dispersion parameters are dependent of the subsurface parameters and the fracture pattern. The three regimes are constructed for a $\kappa_{\text{frac}}/\kappa_{\text{m}}$ permeability ratio between $8 \times 10^3$ and $8 \times 10^6$.
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Chapter 1

Introduction

The focus of this thesis is geothermal energy and will be discussed in three chapters.

First, a more practical side of the production of geothermal energy is discussed. I look into the possibilities of producing geothermal energy in Noord-Brabant in the Roer Valley Graben. The geological background, the interesting aquifers and the surface demands and restrictions are discussed to give an advice about the area.

The second part of this thesis discusses the influence of fractures on the geothermal heat production. Different fracture patterns are designed in a numerical finite element program and I look at the variations in the breakthrough, life time and cool down time due to the fracture patterns. A simple heat transport equation is fitted to the breakthrough curve of the numerical experiments by changing the apparent thermal dispersion. The apparent thermal dispersion is compared to Peclet to find the relation between the thermal dispersion and Peclet.

In the last section the implementation of the research from the second part is discussed. Chapter 2 and 3 can both be read as stand alone chapters.
Chapter 2

Geothermal Energy in the Roer Valley Graben

This chapter looks into the potential of a specific location for the exploitation of geothermal energy. The area of interest is Noord-Brabant in the south of the Netherlands. In the past a study into the possibilities of this area has been conducted. That study was sponsored by the public drinking water company 'Brabant Water' and the municipalities of Tilburg, Breda, Eindhoven and Helmond and was executed by IF Technology (Maaijwee et al., 2012). The study gives a general indication of possible locations for the production of geothermal energy. In a second assignment IF studied the possibilities to produce heat from the large faults in the area and looked into the geochemical aspects of the area (Drijver, 2014). The studies from IF technology focus on the Triassic and in particular the early Triassic sands. The Triassic sandstone layers are also the focus of this thesis.

This chapter gives a broad description of the geological background and a specific location is evaluated with the available data and restriction on the surface and in the subsurface.

2.1 Geological Background

2.1.1 General Structure

In the south of the Netherlands two large basin structures are present, the Roer Valley Graben (RVG) and the West Netherlands Basin (WNB). The RVG is asymmetric and stretches from Euskirchen in Germany to ’s Hertogensbosch in the Netherlands. The RVG is part of the north-western branch of the Rhine Graben rift system (Geluk et al., 1994) and follows into the West Netherlands Basin around the boundary between the
provinces, Noord-Brabant and Zuid-Holland. The WNB is mainly present in Zuid-Holland and offshore. The basins are developed in the Permian Triassic times and have a NW-SE direction.

In the south, the Roer Valley Graben is bounded by the Londen-Brabant Massif and on the east by the Rhenish Massif \cite{Geluk1996}. At those boundaries, large fault structures are located such as the active Peel Boundary Fault in the north-east and the Feldbiss Fault and the Beringen Fault in the south-western. The Beringen Fault follows into the Rijen Fault. The throw of the area is between 100 and 400 m in the south-western area and up to 1000 m at the Peel Boundary \cite{Geluk1994}.

Figure 2.1 shows an overview of the area with the structural framework.

The Roer Valley Graben is divided into tectonic units. This is based on the Cenozoic subsidence pattern. From south-west to north-east the following blocks are present \cite{Geluk1994}:

- The Brabant Massif:
- The Eastern and Western Campine blocks
- The Roer Valley Graben and the Erft blocks
- Venlo block, the Peel bloc and the Köln block
- The Krefeld Block

The blocks can be found in figure 2.2.
Figure 2.2: Overview of tectonic blocks in the Roer Valley Graben [Geluk et al., 1994]
2.1.2 Tectonics and Stratigraphy

The contours of the Roer Valley Graben formed during the Carboniferous due to the Variscan displacement along the Peel Boundary Fault. Later, during the Permian, no subsidence of the graben occurred and the RVG acted as a fault bounded platform.

On top of the Upper Carboniferous deposits a thick Permian-Triassic-Jurassic sequence can be found in the RVG. Outside of the graben much of these deposits have been eroded due to Middle Jurassic to Cretaceous erosion (Geluk et al., 1994).

The deposits of the Triassic show a pronounced layer-cake character on a reservoir scale (Geluk et al., 1996). In the middle of the Roer Valley Graben the thickness of the Triassic is around 950m. The largest part is made up by the Lower Triassic sand and clay stones of 700 m with 350 m as the Lower Buntsandstein, 200 m as the Main Buntsandstein and 150m as the Upper Buntsandstein, this includes the Solling and the Röt. Towards the Peel and Eastern Campine Blocks the Triassic sequence is smaller due to the Late Kimmerian erosion (Geluk et al., 1994).

During the Triassic a rapid subsidence of the graben floor occurred. Seismic data also shows little syndepositional faulting so the subsiding area was not bounded by the faults. A pull-apart basin was created that was limited by east-west trending strike slip faults. The Peel and Campine Blocks were uplifted during the Middle Jurassic till the Early Cretaceous. These large scale uplifts are linked to the regional uplift of the Brabant and Rhemish Massifs. The uplift events are described by the Late Kimmerian tectonic phase and created an uplift of at least 2000 m of the Brabant Massif (Geluk et al., 1994, 1996). During the Triassic also a smaller tectonic event occurred, the Hardegsen phase. This phase, that comprises up to four short-lived rift pulses, created a large erosion in the area and affected the thickness and the sand dispersal patterns of the main Buntsandstein (Geluk, 2007) (Bachmann et al., 2010, p. 158).

During the Sub-Hercynian tectonic phase in the Late Cretaceous the Roer Valley Graben underwent tectonic inversion. The inversion created uplift for all the Jurassic and older basins and the uplifted sediments suffered under erosion. The faults that were active during the late Kimmerian tectonic phase now acted as reverse faults (Geluk et al., 1994).

TNO conducted a research into the burial depth of the Triassic. The conclusion of this research was that the sediments are now at its deepest location (Loveless et al., 2013; Maaijwee et al., 2012). This conclusion makes the interpretation of the cores much easier since now a linear relation between porosity and depth can be assumed (Maaijwee et al., 2012).
2.1.3 Depositional Environment

In the Netherlands the Triassic rocks are mainly deposited in a continental environment. At the beginning of the Triassic, the Netherlands was part of a shallow sea with high salinity. The climate was very hot and dry and alternated with some wet periods. In the middle of the Netherlands a brackish to fresh water lake emerged. Around the shallow parts of the lake, fine grained sediments were deposit and oölites were formed. Oölites are round chalk nodules that have a diameter of maximum 1 cm. They are formed due to the shallow water movements. During the dry periods the shallow parts dried up and the wind deposited sand which formed dunes (de Mulder et al., 2003).

The early Triassic was dominated by a uniform submerging of the South Permian basin. During the Variscan, mountains were formed and in the rainy periods large rivers from these mountains flowed to the north and dragged large grained debris to the plains.

During the Early to Middle Triassic, the Roer Valley Graben was used as the main feeder system from the Paris Basin to the sea. The sediments came from the London-Brabant massif. Due to this system, 200 m of massive sandstones and conglomerates were deposited in the Roer Valley Graben and on the Peel Block. These layers are covered by a thick layer of clay stones (Geluk et al. 1996).

Figure 2.3 shows an overview of the facies distribution. The indicated boundaries of the lower fan and the alluvial fan are not fixed, however the figure shows an indication of the depositional environment (Maaijwee et al. 2012). In the centre of the graben a braided fluvial system was formed. The sediments carried by the river, came from the south-west and north-east mountain area. The absence of significant large conglomerates indicates an alluvial fan distribution. The core description of one of the wells in this area (HSW-01) also indicates a continental environment where dry periods are being alternated with high energy rivers and can be best described as a wadi (Bilt, 1992).

2.1.4 Sedimentary Facies

In the Netherlands the Triassic is divided between the Lower Germanic Triassic Group and the Upper Germanic Triassic group (Geluk et al. 1996).

The Upper Germanic Triassic consists of the following facies (Van Adrichem Boogaert and Kouwe 1993-1997):

- Keuper Formation
- Muschelkalk Formation
- Röt Formation
- Solling Formation

The Lower Germanic Triassic Group overlays the Zechstein Group and includes all the sediments up to the unconformity at the Upper Germanic Triassic Group. The upper
boundary is placed at the base of the Solling Sandstone member. The Lower Germanic Triassic Group only holds the Main Buntsandstein with the following facies (Van Adrichem Boogaert and Kouwe, 1993-1997):

- Hardegsen Formation
- Detfurth Formation
- Volpriehausen Formation
- Lower Buntsandstein Formation
  - Rogenstein Member
  - Main Claystone Member
  - Nederweert Sandstone Member

The thickness and distribution of the facies are strongly influence by the erosion of the Hardegsen phase in the RVG, with the Detfurth unconformity as the most prominent unconformity (Geluk et al., 1996).

Below, the facies are described, started with the oldest one going upwards.

Lower Buntsandstein Formation
During the Lower Buntsandstein the Dutch basin was filled with clastics coming from the Ardenne-Eifel fluvial system through the Roer Valley Graben. The sediments were transported through the Ems Low into the North German Basin (Geluk et al., 1996). The formation consists of cyclic alternation of fine grained lacustrine sandstones and
clay-siltstones. The sequences are fining upward and have a thickness of 20 to 40 m. In Limburg the sequence consists of conglomerates, but not in the north-west part of the Roer Valley Graben (Geluk, 2007).

Volpriehausen Formation
The Lower Volpriehausen can be indicated as a clean sandstone. The quartz percentage is slightly below 50 percent and the lowermost parts of the formation have high percentages of calcite and dolomite cement. The Upper Volpriehausen Sandstone is a reddish-brown silty sandstone with dolomite, anhydrite and ankerite cements. The cycles are stacked fining-upwards. The uppermost sandy part is present in the Roer Valley Graben (Geluk, 2007).

Detfurth Formation
The Lower Detfurth has the best reservoir qualities, it has up to 60 percent quartz content. In the Roer Valley Graben the thickness of the Detfurth formation is limited due to erosion (Geluk et al., 1996).

Hardegsen Formation
The Hardegsen formation is characterized by a rapid alternation of sandstones and claystones (Geluk et al., 1996). In the Roer Valley Graben the sequence has a maximum thickness of 70 m.

Solling Formation
The Solling was deposited on older deposits due to the Hardegsen and Basal Solling unconformity from the Hardegsen phase. The Solling formation consists of the Basal Solling sandstone and the Solling claystone. The Basal Solling sandstone has some potential, however the Solling claystone is the first laterally extensive claystone above the main Buntstandstein and has no potential (Geluk et al., 1996).

Röt Formation
The Röt formation consist of an evaporatic lower part. In the south of the Netherlands, the upper part consists of sandstones and the salt distribution is minimal. Geluk (2007) claims that the Röt sandstone is a very promising reservoir with excellent porosities.

Muschelkalk Formation
The Muschelkalk consists of carbonates and evaporates from a marine environment. In the Roer Valley Graben the Muschelkalk formation consists of salt. The top is eroded due to the Late Triassic erosion. The occurrence of salt and the erosion makes the Muschelkalk not an interesting reservoir (Geluk et al., 1996).

Keuper Formation
The Keuper formation consists of a clay stone and is not interesting for a geothermal reservoir (Geluk, 2007).
2.2 Aquifer Properties

In het Brabant Brede Onderzoek an extensive research is conducted into the potential of Noord-Brabant (Maaijwee et al., 2012). In that report different relations were developed to determine the porosity and permeability at certain depths. Those relations will be used for this thesis. The data that was used by Maaijwee et al. (2012) came in large extend from nlog.

2.2.1 Aquifer Layers

In Noord-Brabant the Triassic mainly consists of sandstones and clay stones. The sandstones are possible reservoirs for a geothermal project due to the porosity and permeability values. The claystones will not have the right reservoir properties for this project. The following layers might have potential in this area.

- Röt Fringe Sandstone Member
- Basal Solling Sandstone Member
- Hardegsen Formation
- Detfurth Formation
  - Upper Detfurth Sandstone Member
  - Lower Detfurth Sandstone Member
- Upper Volpriehausen Sandstone Member
- Lower Volpriehausen Sandstone Member
- Lower Buntsandstein Formation
  - Nederweert Sandstone Member

With different measurements, the permeability and porosity of the cores were calculated and Maaijwee et al. (2012) used those measurements to determine a relations between the porosity & depth and the porosity & permeability. Only for the Röt Fringe Sandstone member, enough information was available to determine a relation for this individual layer. Maaijwee et al. (2012) took the values of the Lower Germanic Triassic Group and the Basal Solling Sandstone together to determine the relations for these layers.

Appendix B shows the relations that are computed by Maaijwee et al. (2012). Maaijwee et al. (2012) assumes linear relations between the depth & the porosity and an exponential relation between the porosity & the permeability. Appendix B also shows the locations of the used data points. Maaijwee et al. (2012) did not found one clear relation in each layer, but observed two relations to describe the relation between depth & porosity. Maaijwee et al. (2012) also constructed two relations between the permeability & the porosity. The distinction is based on the porosity value. Maaijwee et al. (2012) attributes the two relations to the different depositional environments seen in figure 2.3.
Röt Fringe Sandstone Member

The small porosity and permeability found in the Röt Fringe Sandstone can be attributed to diagenetic processes and strong cementation \cite{Loveless2013}. The research of Loveless et al. \cite{Loveless2013} focussed on the Röt Fringe Sandstone member around Waalwijk and found a variation in cementation phases. They claim that these variations could be the reason that Maaijwee et al. \cite{Maaijwee2012} found multiple relations between the porosity & depth and between the porosity & permeability. Loveless et al. \cite{Loveless2013} also indicates that it is possible that the cements, dolomite and anhydrite are not present at certain locations, which would lead to higher values of porosity and permeability.

Loveless et al. \cite{Loveless2013} indicates that if there are fractures in the Röt Fringe sandstone, they are likely to be filled with fine-grained low permeability material and will likely baffle the fluid flow instead of focussing it. However if the fractures are open, they could increase the permeability \cite{Loveless2013}.

The study from Loveless et al. \cite{Loveless2013} also concludes that there are differences in cementation between the cores from wells closer and further away from the fault zone. More dolomite was found close to the fault zones and more anhydrite was present further away from the faults. Acid could be injected to increase the permeability of the dolomite cemented zones.

Lower Germanic Triassic Group and Basal Solling Sandstone

Maaijwee et al. \cite{Maaijwee2012} combined the information of the Lower Germanic Triassic Group and the Basal Solling Sandstone to constructed the relations between the depth & porosity and porosity & permeability (Appendix B). Unfortunately the available information on these sandstones is minimal so an extensive study such as the study from Loveless et al. \cite{Loveless2013} could not be conducted for the Lower Germanic Triassic group and the Basal Solling sandstone.

2.2.2 Geothermal Gradient

The relation between the depth and the temperature can also be found in Appendix B.

2.2.3 Fractures

Smaller fractures are often found around large faults, \cite{Faulkner2010}. Loveless et al. \cite{Loveless2013} pay some attention to the occurrence of fractures in the Röt Fringe Sandstone member around the Waalwijk field. That report concludes that the fracture are likely to be closed in the Waalwijk field due to cementation.

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Nieuwland (2013) conducted a study into the properties of the faults in the region of Tilburg where a 3D seismic survey was available. Nieuwland (2013) concludes that the east-west orientated faults in this area will probably be sealed. The north-south orientated faults could be leaking in some sections and act as a connecting zone between reservoir blocks, however with limited permeability. Nieuwland (2013) also concludes that fractures could be expected with outer-arc extension and the reservoir permeability could be larger in these areas. An advice is to conduct a curvature analysis to identify those zones.

2.3 Target Locations

The area around Tilburg is the target location in this thesis. This location is located in the permit area of Hydreco and a 3D seismic study is available in this region. Figure 2.4 shows the permit location (in yellow) and the seismic 3D study that is available (pink). The figure also shows the 2D digital seismic lines and the wells that were drilled in this area. A grey circle stands for a well that did not reach into the Triassic, a blue balloon indicates a well that did reach into the Triassic. A blue balloon with a black dot means that at that location, there are cores available at Triassic depth.

Another reason to pick the area around Tilburg as the target, is that the location is located at the flanks of the Roer Valley Graben and this is indicated as a possible location for geothermal energy production by Maaijwee et al. (2012).

Maaijwee et al. (2012) also indicated Helmond as an interesting area. At that location, there are only 2D seismic lines available and the lines give limited information. The amount of previous drilled wells is also limited at that location. Due to the lack of information of this location, no research is conducted into that area.

2.3.1 Surface Requirements

In this project the surface location is very important since the heat will have to be distributed. The surface location of the doublet should be located as close as possible to a distribution point. To determine a correct surface location the constraints listed below should be taken into account.

Clients

On the surface the heat needs to be distributed to clients that want to buy the heat. The following clients could be taken into account is this area:

- Greenhouses
  Positive: Greenhouses don’t need high temperatures (45 °C) and there are loca-
Figure 2.4: Overview of the permit location (yellow) and the area with available 3D seismic (pink). The lines show the available 2D seismic lines, the blue boreholes indicate a location with information about the interesting reservoir layers. A dark spot in the blue balloon indicates that core measurements were executed at this location.

- Industry
  Positive: The industry needs large amounts of heat.
  Negative: The temperature depends on the client.
  It is difficult to find a company that is willing to commit itself to a certain location for the lifetime of a geothermal doublet.

- Households
  Positive: If there is a deal with a housing association, a lot of houses can be connected. Contracts can be made for a long time.
  Negative: Often the heat installation in a house needs a high temperature (95 °C). The heating installation of a house will have to be changed to use geothermal energy or extra heat will have to be added.

**Infrastructure**

The Amer Centrale is a large heat station nearby Made that provides heat for all the three subgroups mentioned above through distribution pipelines. A possibility for the
distribution of the heat is to supply it into the existing pipelines.

**Drink Water Subtracting Areas**

The drinking water subtracting areas are areas that are protected and strong demands are made towards the activities on the surface. Often a large area around the subtracting area is declared as a no-drilling area.

There is a drinking water subtracting area around Tilburg, the Gilzerbaan drinking water subtracting area that is located south-west of Tilburg. This area is also bounded by a large no-drilling zone. Figure 2.5 shows the location of the no-drilling zone on the surface.

**2.3.2 Subsurface Requirements**

The 3D seismic survey gives a lot of information about the subsurface around Tilburg. Figure 2.6 shows the top Posidonian and figure 2.7 shows the top of the Triassic. The Posidonian shale generates a seismic event that can be detected easily due to a major change in density compared to the surrounding layers. The Posidonian shale lays on top of the Triassic in the early Jurassic. The resolution of the seismic detection of the Triassic was limited under the city of Tilburg so for that reason both maps are shown here.

Nieuwland (2013) looked into the sealing capacity of the faults. This study is shown in the map of the top Posidonian (figure 2.6). The faults that are indicated with red lines

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are highly sealing faults, the blue faults are likely to seal and the faults in yellow are probably leak.

To get an indication of the depth of certain layers, several wells around Tilburg that have information about the Triassic are analysed. The information is combined in figure 2.8 that shows the true vertical depth (TVD) of the different reservoir layers at each well location. The location of the wells can be found in figure 2.9.

Figure 2.8 shows that the Röt Fringe Sandstone member is one of the thickest layers and present over the full interval. Maaijwee et al. (2012) indicated the Röt Fringe Sandstone member as a promising aquifer. The Upper Volpriehausen Sandstone member is also thick and present at a lot of location, only Loveless et al. (2013) indicated the Upper Volpriehausen Sandstone Member as a limited aquifer.
2.3. TARGET LOCATIONS

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Figure 2.6: Depth map of the Posidonian shale with the open en closed faults indicated (Nieuwland 2013)
Figure 2.7: Depth map of the Top Triassic [360Plus Consult 2013]
Figure 2.8: The depth of certain aquifer layers at each well, the interesting reservoir layers are indicated in colours.
2.3. TARGET LOCATIONS

CHARTER 2. ROER VALLEY GRABEN

Even though the information that is used in Maaijwee et al. (2012) is limited for some of the aquifers, the relations that are shown in appendix B are used to determine the potential of the different locations. The average permeability is multiplied with the thickness to calculate the transmissivity. Besides the transmissivity, the temperature is also plotted in figure 2.10.

Figure 2.10 shows that a high temperature is associated with a low transmissivity because a high temperature means a deep location and the permeability rapidly declines with increasing depth. Maaijwee et al. (2012) indicated that a transmissivity of minimal 2 Dm is needed. The only wells that meet that requirement are SPC-01, HBV-01, BKZ-01 and HVB-01. The properties of the Röt Fringe Sandstone at these locations can be found in table 2.1.

To determine a location, the thickness of the sandstones needs to be known to determine the minimum permeability.

Gas and Oil Fields

There is a gas field in the area, the Waalwijk field. Figure 2.9 shows the wells that extract gas from the field (WWN, WWK and WWS). The gas comes from the Buntsand-
2.3. TARGET LOCATIONS

<table>
<thead>
<tr>
<th></th>
<th>SPC-01</th>
<th>HBV-01</th>
<th>BKZ-01</th>
<th>HVB-01</th>
</tr>
</thead>
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<tr>
<td>From below NAP [m]</td>
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<td>1903</td>
<td>2257</td>
<td>2150</td>
</tr>
<tr>
<td>To below NAP [m]</td>
<td>2334</td>
<td>1953</td>
<td>2327</td>
<td>2224</td>
</tr>
<tr>
<td>Thickness [m]</td>
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<td>50</td>
<td>69</td>
<td>74</td>
</tr>
<tr>
<td>Permeability [D]</td>
<td>0.3</td>
<td>0.9</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>90</td>
<td>76</td>
<td>89</td>
<td>86</td>
</tr>
</tbody>
</table>

Table 2.1: Properties of the Röt Fringe Sandstone around for wells SPC-01, HBV-01, BKZ-01 and HVB-01

Figure 2.10: The transmissivity and temperature of the potential layers at different well locations
2.3. Choice of Location

The restrictions and interesting locations at the subsurface and surface can be combined in a map (figure 2.11):

- The doublet needs to be in close range of a distribution location. (Blue area)
- In most of the areas the Triassic is located too deep to economically produce geothermal energy.
- Maaijwee et al. (2012) indicated that with an average thickness of 250 m of the sandstones, the maximum depth is 2800 m. The Triassic is on average 350 m thick, so the top Triassic can not be located lower than 2450 m (Pink area).
- The doublet can not be placed in the no-drilling zone. (Black area)
Another constraint is the gas field in the north. If the doublet is placed too much to the north, gas might be produced.

The area that combines the requirements and does not fall into the restrictions, is the narrow horst in the middle of figure 2.7. This horst has a width between 1 and 2 km. Well HBV-01 is drilled into this horst and gives an indication of the sandstone layers in place. The promising Rot Fringe Sandstone and Lower Volpriehausen Sandstone are present at this location, together with the Lower Derfurth Sandstone. Figure 2.12 shows a schematic overview of the aquifer layers and their depth from north to south. The no-drilling zone and well HBV-01 are indicated. The development of the layers is based on the seismic map in figure 2.7, the thickness is taken from well HBV-01. The layers deepen rapidly north of well HBV-01.

The maximum depth of the Triassic is dependent on the permeability at that location. The total thickness of the sandstone layers is almost 190 m in HBV-01 so the permeability needs to be above 0.01 D to produce enough heat. A minimum permeability of 0.01 D correlates to a depth of 2700 m according to Maaijwee et al. (2012). Between the top of the Triassic and the bottom of the Lower Volpriehausen Sandstone is almost 350 m. The Top of the Triassic needs to be above 2350 to meet the requirements.

The Orientation of the Doublet

Since the only interesting block is the narrow horst the doublet can only be placed in north-south direction to secure distance from the faults. If the doublet is placed in another direction, the injector could inject cold fluid into the fault. To minimize the needed pressure for the re-injection the injector can be placed higher in the aquifer than the producer.

2.4 Risks and Additional Studies

As indicated by Loveless et al., (2013) the location is not without risks. A large part of the Roer Valley Graben is limited in its geothermal potential due to the sediment compaction since the sediments are at large depths. Multiple relations were found for the depth & porosity and the porosity & permeability by Maaijwee et al. (2012). Loveless et al. (2013) concluded that these variations occurred due to tectonic and diagenetic evolution. The study from Loveless et al. (2013) focussed on the wells in the Waalwijk field (WWN-01-S2, WWN-03 and WWK-01). These wells are located in a different fault block, so it is difficult to predict how the properties that were measured there can be related to the narrow horst.
Figure 2.12: Schematic cut through of the horst with the layers in place derived from well HBV-01 and the depth is based on figure 2.7.
2.5 Increasing Permeability

At the indicated location, the Lower Volpriehausen and the Lower Detfurth Sandstone members are the thickest and the most promising sandstone members. However, the information about these layer is limited and the permeability values that are obtained for this location are based on the properties of multiple sandstone members. More research should be conducted into these layers to obtain reliable permeability data.

An additional study should be constructed into the net to gross of clay. Large clay stones are found and it is interesting to know what the net total thickness of sandstones will be.

2.5 Increasing Permeability

The choice of the location is limited due to the depth of the Triassic that determines the permeability. The number of possible locations would increase if the permeability would increase. Since there are many faults in the area, the existence of fractures is likely. [Faulkner et al., 2010]. [Loveless et al., 2013] indicated that most fractures in this region are closed due to cementation. According to the authors, the fractures close to the faults are cemented with dolomite that can be dissolved with acid. [Nieuwland, 2013] indicated that fractures would not only exist close to the fault, but also at a location that underwent outer-arc extension. Fractures increase the permeability however, they are also the cause of early cold water breakthrough. Therefore the next chapter will look into the effects of fractures to indicate if and how they can change the heat production.
Figure 2.14: Area between the red lines is where the Triassic is above 2000 m depth. This location is based on figure 2.13 and shown on the surface around Tilburg.
Chapter 3

Influence of Fractures on Geothermal Heat Production

3.1 Introduction

In the Netherlands, geothermal energy starts to gain more interest as a heat source in the greenhouse industry and for the heating of homes and buildings. In some areas of the Netherlands the essential features for the economic exploitation of a geothermal reservoir are likely to be found: A thick (sandstone) aquifer with enough permeability, a sufficient temperature and a supply market on the surface. In the South of the Netherlands, around the city of Tilburg one of these areas can be found. Here, the thick sandstone layers from the Triassic on the flanks of the Roer Valley Graben may have the essential features for geothermal exploration. The area is characterised by a large number of faults that might have generated smaller fractures around these faults (Faulkner et al., 2010). Nieuwland (2013) indicates that at this location fractures could also be expected due to outer-arc extension.

If the fractures are highly conductive, they can enhance the heat production by increasing the effective reservoir permeability \( (\kappa_{\text{eff}}) \) but they may also be the cause of early cold-water breakthrough by providing fast flow pathways. On the other hand, closed fractures can create barriers for the fluid percolation. Both open and closed fractures change the fluid flow behaviour significantly.

Transport in a homogeneous reservoir is modelled with a standard Fourier or Fickian transport equation. The equation can be used to describe various types of transport, such as solutes and heat. The equation is called the Advective-Diffusivity Equation (ADE) and uses advection and diffusion to describe the transport (Bejan, 1993). The advective process describes the displacement of the center of the movable mass and the diffusive process describes the spreading of the mass around the center. In heat transport, the diffusive process describes two processes, the diffusivity, that is described by the heat
conduction (diffusion) and the heat dispersion (Ciriello et al., 2013).

The thermal diffusion describes the process of molecular diffusion, a process where the energy of the molecules is transferred to the surrounding matrix or fluid. This influences mainly the front of the injected fluid (Perkins and Johnston, 1963). Heat dispersion is often neglected in heat transport due to the domination of thermal diffusion (Molina-Giraldo et al., 2011; Rau et al., 2014). While the conduction takes place in both the fluid and the rock matrix, dispersion only takes place in the fluid phase (Perkins and Johnston, 1963). Dispersion occurs due to variations in flow paths and the velocity at the pore scale caused by heterogeneity in the system (Berkowitz and Scher, 1995; Molina-Giraldo et al., 2011; Ruiz Martinez et al., 2014; Saeid et al., 2014).

In addition to the discussion about the relevance of thermal dispersion, there is also an important discussion on the way dispersion is described and its dependency on the fluid velocity. One of the first theoretical studies on thermal dispersion already concluded that dispersion can vary significantly (Rau et al., 2014; Zeng-Guang et al., 1991) and today this has resulted in the multiple descriptions of thermal dispersion. Some of these models suggest a linear relation (Geiger and Emmanuel, 2010; Keller and Roberts, 1999; Saeid et al., 2014; Sauty et al., 1982), while others have identified a non-linear relation (Lu et al., 2009; Metzger et al., 2004; Rau et al., 2012).

Normally the ADE is sufficient to describe fluid flow and transport in a strongly homogeneous reservoir (Lu et al., 2009; Rau et al., 2012; Ruiz Martinez et al., 2014) however, when heat transfer through a porous media cannot be represented with the ADE using effective parameters such as effective permeability and effective dispersivity, the behaviour of the system is labelled as ‘non-Fourier-like’, ‘Non-Fickian’ or ‘anomalous’. For solute transport a framework is developed to describe this ‘non-Fourier-like’ behaviour. It is called the Continuous Time Random Walks (CTRW) framework and it is developed to describe the transport of solutes in fractured and heterogeneous porous media. Many studies have shown that the framework is successful describing the behaviour of solute transport in numerical models and laboratory set-ups (Berkowitz et al., 2002; Bromly and Hinz, 2004; Cortis and Birkholzer, 2008; Deutz et al., 2004; Di Donato et al., 2003; Eldery et al., 2014; Geiger and Emmanuel, 2010) and Emmanuel and Berkowitz (2007) have shown that the CTRW framework can be used successfully for heat transfer. Emmanuel and Berkowitz (2007) focussed on the general application of the method in heat transfer and Geiger and Emmanuel (2010) focussed only on two fractured reservoirs and determined that CTRW could describe ‘non-Fourier’ behaviour better compared to the ADE. They also concluded that connectivity is the factor that mainly influences the heat transport behaviour and that a fractured model with higher connectivity results in a better representation by the ADE.

In contrast to solute transport, there is limited number of studies on heat transfer in fractured rock. In this study the goal is to explore the influence of fractures on geothermal heat production. To do this: a heat Discrete fracture model (DFM) is extended for heat transfer and several conceptual fracture networks are designed. In this the-
sis the focus is placed on open, conductive fractures and no attention will be paid to close fractures. The behaviour of the models is simulated with the Advective-Diffusivity Equation. Taken into account explicitly the presence of fractures, the question arises if the ADE, solved for an effective porous media (EPM), is able to represent heat transfer in a heterogeneous fractured reservoir. If the ADE is not able to cover the Non-Fourier behaviour the CTRW framework is applied to find an accurate fit. Subsequently, the effective dispersion coefficients are calculated and a relation between the thermal dispersion and the velocity is described by comparing different thermal dispersion models. Further, the effects of the different fracture patterns on the breakthrough time, lifetime and the time that is needed to cool down the total system, are discussed.

3.2 Governing Equations

The following section describes the various equation that are used in this thesis.

3.2.1 Advection - Diffusivity Equation

The Advective-diffusivity equation is based on Fourier’s law:

\[ q_h = -\lambda \nabla T \]  

(3.1)

Fourier’s law describes the heat transport \( q_h \) that is caused by a temperature difference \( \nabla T \) multiplied by the thermal conductivity of the media \( \lambda \). This is called heat transfer through heat conduction.

By substituting this equation in the following local energy balance equation:

\[ \nabla \cdot q_h = -\rho c \frac{\delta T}{\delta t} \]  

(3.2)

the heat conduction equation reads:

\[ \frac{\delta T}{\delta t} = D \nabla^2 T \]  

(3.3)

where \( D \), the diffusivity can be described as \( D = \lambda/\rho c \) \cite{Abdel-Hamid1999}. The parameter \( t \) describes the time [s], \( \rho \) [kg/m\(^3\)] describes the density and \( c \) is the specific heat capacity [J/(kg K)] of the medium that conducts the heat.

To determine the advection part, assumed is that the fluid is incompressible. That leads to the following equation:

\[ \frac{\delta T}{\delta t} = v_h \nabla T \]  

(3.4)
Combining equation 3.3 and 3.4 the ADE is found (Bejan, 1993):

\[
\frac{\partial T}{\partial t} = v_h \nabla T + D \nabla^2 T \tag{3.5}
\]

Here \(v_h\) describes the heat velocity. This equation is similar to the solute transport equation:

\[
\frac{\partial s_{sc}}{\partial t} = v_{sc} \nabla s_{sc} + D \nabla^2 s_{sc} \tag{3.6}
\]

Where, the parameter \(v_{sc}\) and \(s_{sc}\) describes the velocity of the solutes and the solute concentration respectively.

Equation 3.5 is a general equation, that can be applied to porous media. The following equation would be used to describe heat transport in the matrix (solid):

\[
\frac{\partial}{\partial t} [(1 - \phi) \rho_s c_s T_s] - (1 - \phi) \nabla \cdot (\lambda_s \nabla T_s) = 0 \tag{3.7}
\]

and in the fluid phase reads:

\[
\frac{\partial}{\partial t} (\phi \rho_f c_f T_f) + \nabla \cdot (\rho_f c_f q T_f) - \phi \nabla \cdot (\lambda_f \nabla T_f) = 0 \tag{3.8}
\]

The fluid phase and solid phase are indicated with subscript \(f\) and \(s\), respectively. Assuming that the rock immediately adopts the temperature of the fluid locally: \(T_s = T_f = T\). Combining equation 3.7 and 3.8 reads:

\[
\frac{\partial}{\partial t} (\rho c T) + \nabla \cdot (\rho_f c_f q T) - \nabla \cdot (\lambda \nabla T) = 0 \tag{3.9}
\]

The parameter \(\phi\) describes the porosity [-]. The Darcy velocity is calculated with:

\[
q = \phi v_{sc} = -\frac{\kappa \partial P}{\mu L} \tag{3.10}
\]

The pressure field is gained by solving the continuity equation:

\[
\nabla \cdot \left( \frac{-\kappa \nabla P}{\mu} \right) = 0 \tag{3.11}
\]
with $\kappa$ as the permeability tensor [m$^2$], $\mu$ as the viscosity [Pa s], the parameter $L$ as the length of the model [m] and $\nabla P$ as the pressure difference [Pa]. For the sake of simplicity, the influence of temperature on the density and viscosity is not taken into account.

From equation 3.9, it is clear that the velocity of the fluid is not the same as the heat transfer velocity. The heat velocity is retarded because the cold fluid adopts heat from the matrix causing the cold front to travel with a different velocity than the fluid. This is called the retardation effect, described by the retardation factor $(R)$. This leads to the following relation between the fluid velocity and the heat velocity in the ADE:

$$v_h = Rq = \frac{\rho_f c_f}{\rho_c} \phi v_{sc}$$

(3.12)

The description of the heat transfer velocity ($v_h$) is fundamentally different from the description of solute transport velocity ($v_s$). Solute transport only uses the fluid flow to transport the solutes and heat transport uses the fluid flow and the matrix.

When focussing on the transport by diffusion, the transport of heat goes much faster due to the use of the matrix, however if the focus is placed on transport by advection, the solutes travel faster since it is not retarded by the matrix (Rau et al., 2012).

The other parameters in the equation 3.9 are described with:

$$\rho c = (1-\phi)\rho_s c_s + \phi \rho_f c_f$$

(3.13)

and

$$\lambda = \lambda_{eq} + \lambda_{dis}$$

(3.14)

The equivalent thermal conductivity is given by (Molina-Giraldo et al., 2011):

$$\lambda_{eq} = (1-\phi)\lambda_s + \phi \lambda_f$$

(3.15)

The thermal dispersion ($\lambda_{dis}$) describes the process of the acceleration of heat that flows through randomly arranged particles. This process has been described extensively for solutes, but has received less attention regarding thermal transport (Rau et al., 2014).

### 3.2.2 Thermal Dispersion

In a 2D model domain, the dispersion can be described in two directions, along with the flow as the longitudinal dispersion and perpendicular to the flow as the transversal dispersion. The Peclet number (Pe) is used to compare different flow regimes. This
3.2. GOVERNING EQUATIONS

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A dimensionless number describes the ratio between the heat displacement by advection and by diffusion. It can be calculated as follows:

\[ Pe = \frac{v_d d_g}{D} \]  \hspace{1cm} (3.16)

Here \( d_g \) [m] describes a characteristic length. A small Peclet number indicates a low velocity and the heat transfer is mainly influenced by conduction which indicates a large diffusion. A high Peclet number assumes a large fluid velocity and most of the heat is displaced due to the fluid flow (Rau et al., 2012).

The Peclet number is used as the controlling parameter in an active debate on the dispersion in solute and heat transport. Lu et al. (2009); Metzger et al. (2004); Rau et al. (2012) and among other authors have concluded that dispersion has a non-linear relation with Peclet. Other authors such as Sauty et al. (1982) postulated that dispersion has a linear relation with Peclet. Detwiler et al. (2000) found three regimes for the longitudinal dispersion for solute transport based on Peclet number (Pe). If \( Pe < 1 \), the molecular diffusion dominates and \( \lambda_{\text{dis}} \) can be neglected. For intermediate Pe, \( \lambda_{\text{dis}} \) is linear dependent of Pe and for large Pe, the dispersion dominates and \( \lambda_{\text{dis}} \propto Pe^2 \). Molina-Giraldo et al. (2011) found that solute dispersion is also dependent of the length of the field.

In the field of thermal transport, less research is conducted into the effect of Peclet on thermal dispersion. In this thesis four different models will be discussed that give a different description of the thermal dispersion in relation with velocity. The different relations that are available are all made for homogeneous samples and limited attention has been paid to fractures. In this thesis I will show how fractures influence the thermal dispersion. Since the breakthrough curves of the numerical models are compared with a 1D ADE, only the longitudinal thermal dispersion will be discussed. It is common to assume that the longitudinal thermal dispersion is larger than the transversal thermal dispersion by an order of 10 (Geiger and Emmanuel, 2010; Saeid et al., 2014), however for solute transport this is disputed (Bijeljic and Blunt, 2007).

A common assumption for dispersion covering solute and heat transport is that dispersion is influenced by the depositional environment. Thermal dispersion parameters are often based on particle size, pore sizes (Saeid et al., 2014) or soil structure (Lu et al., 2009). The size of the thermal dispersion parameters can also be influenced by the grid size in a numerical model, since thermal dispersion is a parameter for the heterogeneities at a smaller scale than the grid blocks (Geiger and Emmanuel, 2010).

The following four models will be discussed in this thesis:

(1) Sauty et al. (1982) uses a simple linear relation between the fluid velocity and the thermal dispersion shown by:

\[ \lambda_{\text{dis}} = \alpha \rho f c f q \]  \hspace{1cm} (3.17)
Here $\alpha$ describes the hydrodynamic dispersivity [m] tensor. The transversal dispersion can be implemented in this relations in various ways (Geiger and Emmanuel, 2010; Rau et al., 2012; Saeid et al., 2014). Equation 3.18 shows what is used in the numerical model (Smith and Chapman, 1983):

\[
\lambda_{\text{dis,xx}} = \rho_f \rho_c f \alpha L q_x^2 + \alpha_T q_y^2 \sqrt{q_x^2 + q_y^2} 
\]

\[
\lambda_{\text{dis,yy}} = \rho_f \rho_c f \alpha_T q_y^2 + \alpha_L q_x^2 \sqrt{q_x^2 + q_y^2} 
\]

\[
\lambda_{\text{dis,xy}} = \lambda_{\text{dis,yx}} = \rho_f c_f (\alpha_L - \alpha_T) \frac{q_x q_y}{\sqrt{q_x^2 + q_y^2}} 
\]

Here $q_x$ and $q_y$ describe the Darcy velocity in $x$ and $y$ direction respectively. The parameters $\alpha_L$ and $\alpha_T$ indicate the longitudinal and transversal thermal dispersion coefficients, respectively.

Other authors assume a power law relation between the thermal dispersion and the Peclet number or the fluid velocity. 

(2) Lu et al. (2009) assumes the following relation:

\[
\lambda_{\text{dis}} = k q^{0.9} 
\]

Here $k$ [m$^2$ K/J] is a fitting parameter that is related to the soil structure such as size, shape and the tortuosity of the soil pores. The empirical power function is based on three different sand types for various flow rates. For example, a sandstone core had a value of 0.0281 for $k$.

(3) Metzger et al. (2004) relates the relative thermal dispersion to the Peclet number with:

\[
\frac{\lambda}{\lambda_f} = \frac{\lambda_{\text{eq}}}{\lambda_f} + \gamma P_e^{1.59} 
\]

where the dimensionless parameter $\gamma$ is assumed to be 0.073.

(4) Rau et al. (2012) shows that for various experiments the thermal dispersion can be approximated with the following relation:

\[
D = \frac{\lambda_0}{\rho c} + \beta_L \left( \frac{\rho_f c_f}{\rho c} q \right)^2 
\]

They do not use $\lambda_{\text{eq}}$ described in 3.15 but uses a bulk thermal conduction $\lambda_0$:

\[
\lambda_0 = \lambda^\phi \lambda^1_{\Phi} 
\]
The parameter $\beta_L$ describes the longitudinal thermal dispersivity and according to Rau et al. (2012) it has a value of 1.478.

In the rest of this thesis the $\alpha$, $k$, $\gamma$ and $\beta_L$ will a be identified as thermal dispersion parameters.

### 3.2.3 Analytical Solution

Equation 3.5 has a well known analytical dimensionless 1D solution given by Ogata and Banks (1961):

$$
\frac{T(x,t) - T_{in}}{T_{inj} - T_{in}} = \frac{1}{2} \left[ \frac{x - v_{hx}t}{2\sqrt{Dt}} + \exp \left( \frac{v_{hx}x}{D} \right) \text{erfc} \left( \frac{x + v_{hx}t}{2\sqrt{Dt}} \right) \right]
$$

(3.23)

With the following boundary and initial conditions:

- $T(0,t) = T_{inj}; \quad t \geq 0 \quad (3.24a)$
- $T(x,0) = T_{in}; \quad x \geq 0 \quad (3.24b)$
- $T(\infty,t) = T_{in}; \quad t \geq 0 \quad (3.24c)$

The initial and injected temperature are indicated with $T_{in}$ and $T_{inj}$ respectively. The parameter $t$ describes the time and $x$ describes the location. The fluid velocity in the $x$ direction is described by $v_{hx}$.

### 3.2.4 Continuous Time Random Walk

Heat and solute transport that behave Fourier-like can both be described with the ADE (equation 3.5 and 3.6). For this reason, Emmanuel and Berkowitz (2007) and Geiger and Emmanuel (2010) assumed that the Non-Fourier behaviour could also be described with the same framework, namely the Continuous Time Random Walk (CTRW) framework. In both papers the Continuous Time Random Walk framework is successfully used to simulate the Non-Fourier-like behaviour of heat transport. Important to understand is that the velocity and diffusion in a Fourier solution are assumed to be time independent (Dentz et al., 2004). The CTRW treats the velocity and diffusion as time dependent by using a probabilistic approach to calculate the motion of particles with the use of a probability density function (pdf) that is dependent on the range of heterogeneities. The large-scale heterogeneities that are resolved are treated deterministically and the small-scale, unresolved heterogeneities are treated stochastically (Cortis and Birkholzer, 2008). The pdf described as $\psi(s,t)$ is created to make sure that a broad distribution of material properties is used to calculate the overall transport (Berkowitz et al., 2006). The pdf denotes the probability that a particle which is entering in a displacement interval at a given time will reach the end of this interval in the time interval between $t$ and $t + \nabla t$ (Margolin and Berkowitz, 2000).
The heat transport equation for the CTRW framework can be described in a Laplace space as (Geiger and Emmanuel, 2010):

\[ u\tilde{T}(s, u) - T_0(s) = -\tilde{M}(u)[v_\psi \cdot \nabla \tilde{T}(s, u) + D_\psi : \nabla^2 \tilde{T}(s, u)] \] (3.25)

with

\[ \tilde{M}(u) = t_1 u \frac{\psi(u)}{1 - \psi(u)} \] (3.26)

The memory function is given by \( \tilde{M} \) using a truncated power law (TPL). The dimensional Laplace variable is given by \( u [1/s] \). The symbol: \( \sim \) indicates the Laplace transformed variable. The TPL can be described as (Emmanuel and Berkowitz, 2007):

\[ \psi(t) = \left[ t_1 (t_1/t_2)\beta \exp(t_1/t_2)\Gamma(-\beta, (t_1/t_2)) \right]^{-1} \times \frac{\exp(-t/t_2)}{(1 + t/t_1)^{1+\beta}}, \quad 0 < \beta < 2 \] (3.27)

Here, \( t_1 \) is the characteristic time for transition between sites. As stated before, the \( \psi \) is the basis of the CTRW equation and determines the nature of the heat transfer. There are various options for the pdf but in this thesis the truncated power law (TPL) is used because it has shown being capable of capturing a large range of transport phenomena (Dentz et al., 2004). The parameter \( \beta \) describes the system’s heterogeneity. If \( \beta \geq 2 \) the system of heat transport is Fourier-like. The parameter \( t_2 \) gives an indication of the time after which the system becomes Fourier-like and this will break off the TPL. The \( \Gamma \) is the incomplete Gamma function. If \( \tilde{M} = 1 \), equation 3.25 becomes the same as 3.5. It should be noted that parameters \( v_\psi \) and \( D_\psi \) are not equal to \( v_h \) and \( D \). A more extensive study of the different parameter is found in (Berkowitz et al., 2006) and goes beyond the scope of this thesis.

### 3.2.5 Quantifying the Fracture Patterns

To quantify the different models, the average density, spacing, connectivity, block size and area of influence are calculated with the following equations.

**Average density** (Wu and Pollard, 1992):

\[ A_d = \frac{1}{A} \sum_{i=1}^{n} \left( \frac{l_i}{2} \right)^2 \] (3.28)

With \( A \) as the area of the model \([m^2]\), \( l_i \) is the length of fracture \( i \) \([m]\), \( n \) is the number of fractures and \( l_0 \) is the side height of the model \([m]\).

**Average spacing** (Wu and Pollard, 1992):

\[ A_s = \frac{A}{l_0 + \sum_{i=1}^{n} l_i} \] (3.29)
3.2. GOVERNING EQUATIONS  

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Average connectivity:

\[ A_c = 1 - \frac{n_i}{n_0} \]  

(3.30)

With \( n_i \) as the number of clusters and \( n_0 \) as the number of fractures. The average connectivity is on a scale of 0 to 1.

Average block size:

\[ A_b = \frac{B_a}{\sum_{i=1}^{B_n} B_i} \]  

(3.31)

With \( B_i \) as the area of a block that is limited by at least 3 fractures and \( B_n \) is the number of blocks. The fractures do not have to be connected, but they do need to be in close proximity of each other.

Average area of influence:

\[ A_a = \frac{A_{infl}}{A} \]  

(3.32)

The average area of influence \( (A_a) \) is on a scale of 0 to 1. With \( A_{infl} [m^2] \) as the area of influence that can be described as:

\[ A_{infl} = \sum_{i=1}^{n} \left( \sum_{j=1}^{n_s} l_i \times L_{infl} \right) \]  

(3.33)

The parameter \( L_{infl} \) is dependent of the spacing between two fractures \( (L_{space}) \) and the length of influence \( (l_{infl}) \). The parameter \( n_s \) is the number of sides of the fractures (generally the number of fractures times 2).

\[ l_{infl} = \sqrt{t_{av} \times \frac{\lambda_{eq}}{pc}} \]  

(3.34)

\[ L_{infl} = l_{infl}, \quad \text{if} \quad L_{infl} < \frac{L_{space}}{2}, \]  

(3.35)

\[ L_{infl} = \frac{L_{space}}{2}, \quad \text{if} \quad L_{infl} > \frac{L_{space}}{2} \]  

(3.36)

B.C.B. Biemans 47 Delft, University of Technology
Where $t_{av}$ is the time it would take for the fluid to reach the end of the reservoir ($t_{av} = L/v_h$) (Marin, 2010).

In equation 3.34 the square root calculates the penetration depth that is caused by the dispersion. To calculate the total area of influence the penetration depth is calculated on two sides of the fracture and multiplied with the total length of a fracture. Most of the models in this thesis consist of multiple fractures and their area of influence can overlap. In that case, the area of influence will only be counted once (equation 3.35 and 3.36).

3.3 Methodology

3.3.1 Model and Set-Up

To simulate flow and heat transfer in a geothermal fractured aquifer, a 2-dimensional model is build in COMSOL 4.3a that uses a finite element approach. Almost all models have the size of 10 m by 5 m. There are only two larger models with a size of 40 by 5 m$^2$ and 20 by 10 m$^2$. The fractures are discretized as lower dimensional elements. Perko et al. (2011) developed a method solving for solute transport in fractured media representing fractures explicitly by lower dimensional elements. I adjusted this method to simulate for heat transport in fractured rock.

Using lower dimensional fractures has great advantages in comparison to the models representing fractures as 2D elements because less grid cells are needed. If the number of grid cells decreases, the computing time reduces significantly. Figure 3.1 shows two different meshes for a model with one horizontal fracture. In the upper model the fracture is modelled using lower dimensional elements: The mesh consists of 3,204 triangular elements. In the lower model, the fracture is modelled using 2D elements. This model consists of 539,408 triangular elements. The big difference between the amount of triangular elements is caused by the very small elements which the 2D fracture requires since the triangular elements need to be smaller than or equal to the aperture of the fracture.

Figure 3.2 shows the two breakthrough curves calculated for both models showing an identical result. Juanes and Molinero (2002) and Holzbecher et al. (2010) also showed successfully that lower dimensional elements can be used to represent 2D fractures.

The numerical model that is used in this thesis has 33k degrees of freedom and a very small relative and absolute tolerance of $1 \times 10^{-6}$. This tolerance is chosen to make sure the numerical dissipation is minimized. A smooth step function is used to provide a gradual temperature change at the inlet from reservoir temperature to injected temperature.

The model is initially filled with water with a temperature of 70 °C ($T_{in}$). The cold
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Figure 3.1: A 2D fracture domain discretized by triangle elements. The fracture is discretized using 1D elements (upper), and 2D elements (lower)

Figure 3.2: Breakthrough curve calculated for two models in which the fracture is discretized using 1D elements or a 2D elements
injected water has a temperature of 40 °C \( (T_{\text{inj}}) \) and is injected from the left side of the system. At the right side the outlet temperature is measured by averaging it over the full outlet. Figure 3.3 shows the set up of the numerical model and table 3.1 lists the model properties used in this study.

The numerical model calculates the breakthrough curves for models with different fracture patterns and varying matrix permeabilities, inlet velocities and aperture sizes of the fractures. At the left boundary, a Dirichlet boundary condition is added to create a constant inlet velocity. At the right boundary \( (L) \) the pressure is set at \( 1.998 \times 10^7 \) Pa. The lower and upper boundary of the set-up are impermeable boundaries to represent no fluid flow conditions. The heat could not leave or enter the system through these boundaries by conduction. A Neumann boundary condition for the temperature is set at the right boundary.

The initial and boundary conditions can be stated as:

\[
\begin{align*}
T(0, y, t) &= T_{\text{inj}}; \quad t \geq 0 \\
T(x, y, 0) &= T_{\text{in}}; \quad x \geq 0 \\
P(L, y, t) &= P_{\text{in}}; \quad t \geq 0 \\
q(0, y, t) &= q_{\text{inj}}; \quad t \geq 0 \\
T(L, y, t) &= -n \cdot \nabla T = 0; \quad t \geq 0
\end{align*}
\]

Table 3.2 shows the different inlet velocities \( (q_{\text{inj}}) \) with the corresponding values of other parameter that are dependent of the Darcy velocity. With the use of Darcy’s law, for the given velocity, pressure drop, viscosity and length of the model, the effective permeability \( (\kappa_{\text{eff}}) \) could be calculated.

### 3.3.2 Models of Numerical Experiments

To understand how fractures influence the heat production, different fracture patterns are designed. The numerical experiments are conducted in two parts:
3.3. METHODOLOGY

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>( \phi )</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>Density Water</td>
<td>( \rho_f )</td>
<td>1000</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>Density Rock</td>
<td>( \rho_s )</td>
<td>2650</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>Specific Heat Capacity Water</td>
<td>( c_f )</td>
<td>4181</td>
<td>J/(kg K)</td>
</tr>
<tr>
<td>Specific Heat Capacity Rock</td>
<td>( c_s )</td>
<td>920</td>
<td>J/(kg K)</td>
</tr>
<tr>
<td>Thermal Conductivity Water</td>
<td>( \lambda_f )</td>
<td>0.6</td>
<td>W/(m K)</td>
</tr>
<tr>
<td>Thermal Conductivity Rock</td>
<td>( \lambda_s )</td>
<td>2.3</td>
<td>W/(m K)</td>
</tr>
<tr>
<td>Longitudinal Dispersion coefficient</td>
<td>( \alpha_L )</td>
<td>( 10^{-3} ) m</td>
<td></td>
</tr>
<tr>
<td>Transversal Dispersion coefficient</td>
<td>( \alpha_T )</td>
<td>( 10^{-4} ) m</td>
<td></td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>( T_{in} )</td>
<td>70 ( ^\circ )C</td>
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</tr>
<tr>
<td>Temperature Injected Water</td>
<td>( T_{inj} )</td>
<td>40 ( ^\circ )C</td>
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</tr>
<tr>
<td>Pressure outlet</td>
<td>( P_{out} )</td>
<td>( 1.998 \times 10^7 ) Pa</td>
<td></td>
</tr>
<tr>
<td>Characteristic length</td>
<td>( d_g )</td>
<td>1 m</td>
<td></td>
</tr>
<tr>
<td>Volumetric Heat Capacity</td>
<td>( \rho c )</td>
<td>( 2.7 \times 10^6 ) J/(m(^3) K)</td>
<td></td>
</tr>
<tr>
<td>Equivalent Thermal Conductivity</td>
<td>( \lambda_{eq} )</td>
<td>2.1 W/(m K)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: The permanent model parameters used for the numerical simulations and ADE

<table>
<thead>
<tr>
<th>( q ) [m/s]</th>
<th>( v_h ) [m/s]</th>
<th>( D ) [m(^2)/s]</th>
<th>( Pe ) [-]</th>
<th>( \lambda_{dis} ) [W/(m K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4 \times 10^{-4} )</td>
<td>( 6.2 \times 10^{-4} )</td>
<td>( 1.39 \times 10^{-6} )</td>
<td>447</td>
<td>1.67</td>
</tr>
<tr>
<td>( 4 \times 10^{-5} )</td>
<td>( 6.2 \times 10^{-5} )</td>
<td>( 8.28 \times 10^{-7} )</td>
<td>75</td>
<td>0.17</td>
</tr>
<tr>
<td>( 4 \times 10^{-6} )</td>
<td>( 6.2 \times 10^{-6} )</td>
<td>( 7.72 \times 10^{-7} )</td>
<td>8</td>
<td>0.017</td>
</tr>
<tr>
<td>( 1 \times 10^{-6} )</td>
<td>( 1.6 \times 10^{-6} )</td>
<td>( 7.68 \times 10^{-7} )</td>
<td>2</td>
<td>0.0042</td>
</tr>
<tr>
<td>( 4 \times 10^{-7} )</td>
<td>( 6.2 \times 10^{-7} )</td>
<td>( 7.67 \times 10^{-7} )</td>
<td>0.8</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

Table 3.2: Inlet velocity and the velocity dependent values that are used in the numerical simulations
1) First, the numerical experiments are conducted to compare the influence of different fracture patterns with a constant fracture aperture size, on heat production. The simulations are conducted with two different inlet velocities: \(4 \times 10^{-5}\) m/s and \(4 \times 10^{-6}\) m/s. The matrix permeability of these simulations varied and are equal to \(1 \times 10^{-12}\) m\(^2\), \(1 \times 10^{-14}\) m\(^2\) and \(1 \times 10^{-15}\) m\(^2\). Table 3.3 shows all the combinations modelled in this work. All the fractures in this part have a fracture aperture size of 1 mm. In total 96 numerical experiments are conducted.

2) The second part focuses on three fracture patterns to study the influence of different inlet velocities and fracture-matrix permeability ratios on heat production. The fractures in these additional numerical models have different fracture aperture sizes, inlet velocities and matrix permeabilities. Table 3.4 shows the 51 simulation scenarios that are made with their corresponding model number. It should be noted that 12 numerical simulations are listed in both tables. For the consistency they are mentioned in both tables. Table 3.4 shows the corresponding number of these numerical models from table 3.3 between brackets. In total, 135 unique numerical simulations are conducted. The models numbers start from 101 in table 3.4 to make a clear distinction between the two parts in the upcoming figures.

The following fracture patterns are designed. An overview of the fracture patterns can be found in figure 3.4.

**Case 1: Orientation**

In case 1, the influence of different orientations on the heat production is examined by creating a single fracture that is orientated in horizontal, diagonal and vertical direction (figure 3.4). The horizontal and diagonal fractures have a length of 8 m. The vertical fracture has a length of 4 m. The modelling of single fractures can also be seen as conceptual representations of mobile/immobile regions in natural fractured rocks (Ruiz Martinez et al., 2014)

**Case 2: Fracture Spacing and Density**

In case 2, the fracture spacing and fracture density are examined. The fracture pattern consist of horizontal fractures that are placed at a distance of 1 m, 0.5 m or 0.1 m from each other. The first three fracture patterns consists of five fractures. In the fourth model, nine horizontal fractures are equally distributed over the width of the model with a spacing of 0.5 m to examine the influence of fracture density. All fractures have a length of 8 m.
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Case 3: Fracture Connectivity

The third model group is designed to study the effects of fracture connectivity on the heat flow. This case consists of six models that all differ in the number of fractures that are connected (clusters). In the first model, all the fractures are separate and not connected forming a big fracture cluster. In the second model multiple clusters are formed with different sizes. In the third model the fracture pattern consists of three clusters of the same size and in the fourth model these clusters are connected. In all four models the upper and lower horizontal fractures are located at the same location. In the last two models all fractures are placed closer together to provide the same distance between all the horizontal fractures. This means that the upper and lower fracture have a larger distance from the upper and lower boundaries and the clusters are placed closer together. In model 6 the three clusters are connected by adding two small fractures.

Case 4: Block Sizes

Four models with different block size distributions are considered. In the first model the fractures are all placed 1 m apart. In the second model, the vertical fractures are placed closer together at a distance of 0.5 m. In the third model the horizontal fractures are placed closer together at a distance of 0.5 m and the vertical fractures have a spacing of 1 m. In model 4 the horizontal and vertical fracture are 0.5 m apart. The last two models show the models without the vertical fractures to explore the influence of the vertical fractures and connectivity.

Case 5: Diagonal Fractures

Case 5 is designed to understand the influence of diagonal fractures with different lengths that are connected at different locations. In the first model, the diagonal placed fractures intersect in the middle on the right. In the second model the intersection is at the right upper corner of the model. The fractures in the third model also intersects in the right corner however, the upper fractures stretch out over the full length of the model.

Case 6: Longer Models

Model FS.3 is extended horizontally to create a horizontal extended model (repetition four times in series). The vertically extended model is created by repeating FS.3 four times in parallel. These two models are the only models with different surface areas. The surface of LM.1 and LM.2 are $40 \times 5 \text{ m}^2$ and $10 \times 20 \text{ m}^2$, respectively.
# Chapter 3. Influence of Fractures

## 3.3. Methodology

<table>
<thead>
<tr>
<th>Fluid Velocity (q [m/s])</th>
<th>4 × 10⁻⁶</th>
<th>1</th>
<th>4 × 10⁻⁵</th>
<th>4 × 10⁻⁴</th>
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<td>Sub case</td>
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<td>Horizontal</td>
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<td>Diagonal</td>
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<td>(3)</td>
<td>(4)</td>
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<tr>
<td>Vertical</td>
<td>FO.3</td>
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<td>1 m 5F</td>
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<td></td>
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<td>(28)</td>
</tr>
<tr>
<td>0.5x1 m²</td>
<td>BS.2</td>
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<tr>
<td>1x0.5 m²</td>
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<tr>
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</tr>
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<td>Middle</td>
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<td></td>
<td>(39)</td>
<td>(40)</td>
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<tr>
<td>Middle Up</td>
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<td>(41)</td>
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<tr>
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<td>(46)</td>
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<td>Vertical</td>
<td>LM.2</td>
<td></td>
<td>(47)</td>
<td>(48)</td>
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### Table 3.3: Part 1: Different cases and their names. The numbers between brackets are corresponding to their model number

<table>
<thead>
<tr>
<th>Fluid Velocity (q [m/s])</th>
<th>4 × 10⁻⁷</th>
<th>1 × 10⁻⁶</th>
<th>4 × 10⁻⁶</th>
<th>4 × 10⁻⁵</th>
<th>4 × 10⁻⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>Sub case</td>
<td>Matrix Permeability (κ_m [D])</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>FS.1</td>
<td></td>
<td>0.001</td>
<td>(101)</td>
<td>(113)</td>
<td>(7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>(102)</td>
<td>(114)</td>
<td>(8)</td>
</tr>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td>(104)</td>
<td>(116)</td>
<td>(126)</td>
</tr>
<tr>
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<td></td>
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<td>(105)</td>
<td>(117)</td>
<td>(23)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>(106)</td>
<td>(118)</td>
<td>(24)</td>
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</tr>
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<td></td>
<td></td>
<td>0.1</td>
<td>(108)</td>
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<td>(128)</td>
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<tr>
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<td>(121)</td>
<td>(33)</td>
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<td></td>
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<td>(112)</td>
<td>(124)</td>
<td>(130)</td>
</tr>
</tbody>
</table>

### Table 3.4: Part 2: Properties and number of the extra numerical simulations. The number between brackets corresponds to the number of the model in table 3.3
3.3. METHODOLOGY

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Figure 3.4: Fracture pattern of the numerical models
3.3. METHODOLOGY

3.3.3 Fitting Procedure

The analytical solution, introduced in equation [3.23], is employed to test whether or not a 1D ADE, solved for an effective porous medium (EPM) model, can describe heat transfer in fractured media. The 1D solution is computed for 1000 points and the numerical production data is interpolated to a string with 1000 points. The temperature that is shown in this thesis is normalized and interpolated in the following manner:

\[ T_{\text{norm}} = 1 - \frac{T_{\text{production}} - T_{\text{inj}}}{T_{\text{in}} - T_{\text{inj}}} \] (3.38)

The parameter \( T_{\text{norm}} \) describes the normalized temperature for one of the three models, the numerical solution, the ADE or the CTRW.

Two different procedures are used to fit the ADE to the numerical production data. The first procedure fits the ADE to the numerical production data by minimizing the absolute error: This is the global ADE solution and is applied to all the numerical simulations. The second procedure fits the ADE to minimize the relative error at the breakthrough temperature (BTT). This is the ADE\(_{\text{BT}}\) solution. Only the models from the first part are fitted to the breakthrough.

The absolute error is calculated as follows:

\[ \epsilon_{\text{abs}} = \sum_{i=1}^{n} |T_{i,\text{model}} - T_{i,\text{num}}|, \] (3.39)

and the relative error with the following formula:

\[ \epsilon_{\text{rel}} = \frac{t_{\text{num}} - t_{\text{model}}}{t_{\text{num}}} \] (3.40)

Here the subscript “model” is the solution that is generated with the ADE, ADE\(_{\text{BT}}\) or the CTRW and the subscript “num” is the results from the numerical experiments.

In contrast to the CTRW, the dispersion is the only fitting parameter for the ADE and the ADE\(_{\text{BT}}\). The velocity is the same as the applied velocity in the numerical experiment.

When the absolute error of the ADE solution is larger than 0.3, the CTRW framework is applied to the numerical simulations. In order to find the CTRW parameters for different models a Matlab toolbox developed by [Cortis et al. 2013] is used. This solution allows to find a fit by changing 5 different parameters: the \( v, D, \beta, t_1 \) and \( t_2 \). The fitting of this solution also concentrated on minimizing the absolute error between the CTRW model and the numerical production data. In total 95 of the 135 unique numerical experiments are modelled with the CTRW.
The ADE, ADE\textsubscript{BT} and CTRW are evaluated on two different aspects.

a) The first aspect that is evaluated, is the absolute error between the model and the numerical production data for the full breakthrough curve.

b) The second aspect looks at the relative error between the numerical simulation and the applied model at a certain temperature. The first temperature is the breakthrough temperature (LT\textsubscript{0.1%}), that is defined at a normalized temperature drop of 0.1 % at the outlet and corresponds to a temperate drop of 0.3 °C. The corresponding time is defined as t\textsubscript{0.1%}. The second two temperatures are dependent of the lifetime of the reservoir. This is the moment that the produced fluid loses its economic value because the temperature is too low. Two temperatures are defined as lifetime temperatures in this thesis, a temperature drop of 10 % (LT\textsubscript{10%}) and of 30% (LT\textsubscript{30%}). The normalized temperature drop correspond to a temperature drop of 3° C and 9 ° C, respectively. The relative error between the numerical data and the model is calculated by comparing the time (t\textsubscript{30%) and t\textsubscript{10%}) that it takes to reach the lifetime temperature.

### 3.3.4 Apparent Thermal Dispersion

The second part focuses on the apparent thermal dispersion found by fitting the ADE to the numerical production data, minimizing the absolute error. The four different methods to describe thermal dispersion, (section 3.2.2) are evaluated. The models that are mentioned in table 3.3 are used to evaluate the influence of fracture patterns on dispersion. The models from part two (table 3.4) are used to study the effect of Peclet and the permeability ratio on thermal dispersion. The permeability ratios (κ\textsubscript{fr} / κ\textsubscript{m}) for different matrix permeabilities and fracture openings are mentioned in table 3.5. The permeability of the fracture is calculated with: \( \kappa_{\text{frac}} = \frac{d^2}{12} \) based on the cubic law (Bear 1972).

### 3.3.5 Breakthrough Time, Lifetime and Cool Down Time

In the last section, the influence of fractures on the breakthrough time (t\textsubscript{0.1%}), life time (t\textsubscript{10%}) and cool down time (t\textsubscript{97%}) will be discussed. The cool down time is defined as the time it takes to cool down the produced fluids to a temperature of 41° C. To compare the models for different inlet velocity, the injected pore volume is used for comparison.

### 3.4 Results

The results are discussed in four sections. First, the fracture pattern parameters are discussed briefly. The second section evaluates the ability of the ADE, the ADE\textsubscript{BT} and the CTRW applied to EPM, to describe heat transfer in fractured rock. The third section shows the effect of different fracture patterns, velocity and permeability ratios...
3.4. RESULTS

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<table>
<thead>
<tr>
<th>$\kappa_{\text{matrix}}$ [m$^2$]</th>
<th>$d_f$ [m]</th>
<th>$\frac{\kappa_{\text{frac}}}{\kappa_{\text{matrix}}}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^{-14}$</td>
<td>0.001</td>
<td>$8.33 \times 10^6$</td>
</tr>
<tr>
<td>$1 \times 10^{-12}$</td>
<td>0.001</td>
<td>$8.33 \times 10^4$</td>
</tr>
<tr>
<td>$1 \times 10^{-11}$</td>
<td>0.001</td>
<td>$8.33 \times 10^3$</td>
</tr>
<tr>
<td>$1 \times 10^{-12}$</td>
<td>0.0001</td>
<td>$8.33 \times 10^2$</td>
</tr>
</tbody>
</table>

Table 3.5: Fracture-matrix permeability ratios. The permeability of the fractures is calculated with the cubic law ($\kappa_{\text{frac}} = d_f^2/12$)

on the apparent dispersion and in the last section the effect of fracture patterns on the breakthrough time, lifetime and cool down time will be discussed.

3.4.1 Quantifying the Fracture Patterns

Table 3.6 shows the calculated values from equation 3.28 to 3.33. The area of influence is only calculated perpendicular to the fracture and since the fractures are not placed from side to side, the $A_s$ is smaller than 1 for all the models.

Interestingly, the models that are supposed to show the influence of spacing (models FS.1, FS.2, FS.3) have the same value for the $A_s$, calculated according to equation 3.29. What indicates that the fracture pattern parameters are limited in showing the diversity of the fracture patterns in values.

The relation between the fracture pattern parameters and the thermal dispersion, breakthrough, lifetime and cool down time are discussed in section 3.4.4.

3.4.2 Simulating Fractured Reservoirs with the Advective Diffusion Equation & Continuous Time Random Walk

To determine when the ADE can simulate heat transfer in a fractured reservoir the thermal dispersion is adjusted to fit to the breakthrough curve that is obtained from the numerical simulations. This fit is evaluated on the global absolute error of the full curve and the relative errors at three temperatures. Figure 3.5 shows the outcomes of the evaluations. The model number on the x-axis shows the numerical simulation that is conducted (table 3.3 and 3.4). The models are sorted on velocity and the Peclet number of the models is also shown in the figure. The corresponding inlet velocities can be found in table 3.2. All the fitted breakthrough curves with the ADE and the CTRW can be found in the Appendix A. Table 3.7 shows the number of simulations that obtained a better fit with the ADE compared to the CTRW or the ADE_{BT}.

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#### CHAPTER 3. INFLUENCE OF FRACTURES

**Table 3.6: Fracture pattern parameters calculated with equation 3.28 to 3.32**

<table>
<thead>
<tr>
<th>Model</th>
<th>$A_d[m]$</th>
<th>$A_s[m]$</th>
<th>$A_c[-]$</th>
<th>$A_b[m^2]$</th>
<th>$A_a[-]$</th>
<th>$A_a[-]$</th>
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</thead>
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<td>FO.1</td>
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<td>3.8</td>
<td>0</td>
<td>0</td>
<td>0.36</td>
<td>0.11</td>
</tr>
<tr>
<td>FO.2</td>
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<td>3.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FO.3</td>
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</tr>
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<td>0</td>
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</tr>
<tr>
<td>FS.4</td>
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<td>0</td>
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<td>0.75</td>
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<td>0.8</td>
<td>0</td>
<td>3</td>
<td>0.8</td>
<td>0.66</td>
</tr>
<tr>
<td>FC.2</td>
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<td>0.6</td>
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<td>0.8</td>
<td>0.66</td>
</tr>
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<td>0.8</td>
<td>0.8</td>
<td>2</td>
<td>0.8</td>
<td>0.66</td>
</tr>
<tr>
<td>FC.4</td>
<td>1.5</td>
<td>0.8</td>
<td>0.9</td>
<td>3.2</td>
<td>0.8</td>
<td>0.66</td>
</tr>
<tr>
<td>FC.5</td>
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<td>0.8</td>
<td>2</td>
<td>0.8</td>
<td>0.58</td>
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<td>0.9</td>
<td>2.8</td>
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<td>0.58</td>
</tr>
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<td>0.9</td>
<td>1.2</td>
<td>0.67</td>
<td>0.34</td>
</tr>
<tr>
<td>BS.2</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td>1</td>
<td>0.67</td>
<td>0.34</td>
</tr>
<tr>
<td>BS.3</td>
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<td>0</td>
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<td>0.28</td>
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<tr>
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<td>1.4</td>
<td>0.8</td>
<td>0.9</td>
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<tr>
<td>DF.2</td>
<td>0.5</td>
<td>1.6</td>
<td>0.8</td>
<td>0.9</td>
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</tr>
<tr>
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<td>0</td>
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<td>0</td>
<td>0.42</td>
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</table>

Inlet velocity $q [m/s] = 4 \times 10^{-6}$ and $4 \times 10^{-5}$
3.4. RESULTS

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Global Fitting

Figures 3.5.a and 3.5.b show the absolute error between the numerical simulation and the ADE, the CTRW or the ADE\textsubscript{BT} simulation. As expected, the CTRW can generally be fitted better to the breakthrough curve than the ADE and the ADE\textsubscript{BT}, due to employing the memory function. The ADE\textsubscript{BT} shows a very poor fit to the numerical simulation.

Relative Error at the Breakthrough Temperature

Figures 3.5.c and 3.5.d show the relative error of the breakthrough time ($t_{0.1\%}$). The relative error is shown as an absolute value. Both the CTRW and the ADE are limited in capturing this moment. In a non fractured reservoir the diffusion determines the development of the breakthrough. A small diffusion creates a very abrupt breakthrough and no tailing. Fractures also cause an abrupt breakthrough however, they also cause long tailing (Dentz et al., 2004). It is difficult for the ADE and the CTRW to describe both effects. The CTRW is very good in covering the tailing (Appendix A), however that creates problems at the breakthrough. The problem with describing both the tailing and the early breakthrough also explains the large global error of the ADE\textsubscript{BT} in figure 3.5.b.

Relative Error at the Lifetime Temperature

Figures 3.5.e and 3.5.f show the relative error at LT\textsubscript{10\%} and figures 3.5.g and 3.5.h show the relative error at LT\textsubscript{30\%}. Again, the relative error is shown as an absolute value. The relative error is significantly smaller in both cases compared to the relative error at the breakthrough (figures 3.5.c and 3.5.d). The error of the ADE and the CTRW are about the same size however, the CTRW provides a better estimation of LT\textsubscript{10\%} and LT\textsubscript{30\%} (table 3.7).

Considering all the different aspects the CTRW, ADE and the ADE\textsubscript{BT} are rated on, the ADE\textsubscript{BT} shows large shortcomings in describing the behaviour of the heat production. Due to this, the parameters and the simulations of ADE\textsubscript{BT} are not further discussed.

Best and worst fit of ADE and CTRW

Figure 3.6 shows the models that could be fitted best and worst with the ADE and CTRW for the first part of the fractured models.

The best fit by ADE is achieved for model 17 (Fracture pattern: FC.2). CTRW is not applied here since the ADE is sufficient and the absolute error is very small between the
Figure 3.5: The relative and absolute error of the ADE, the CTRW and the ADE_{BT}. 
a) Global fit ADE & CTRW, b) Global fit of the ADE & the ADE_{BT}, c) Relative fit ADE & CTRW at LT_{0.1%}, d) Relative fit ADE & ADE_{BT} at LT_{0.1%}, e) Relative error ADE & CTRW at LT_{10%}, f) Relative error ADE & ADE_{BT} at LT_{10%}, g) Relative error ADE & CTRW at LT_{30%}, h) Relative error ADE & ADE_{BT} at LT_{30%}. The Peclet number is indicated (table 3.2).
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Table 3.7: The number of models that the ADE could simulate the numerical solution better than the CTRW (a, c, e, g) or the ADE\textsubscript{BT} (b, d, f, h) see figure 3.5

<table>
<thead>
<tr>
<th>Case</th>
<th>ADE compared to CTRW</th>
<th>ADE is better in n cases</th>
<th>Case</th>
<th>ADE compared to ADE\textsubscript{BT}</th>
<th>ADE is better n cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>95</td>
<td>8</td>
<td>b)</td>
<td>96</td>
<td>85</td>
</tr>
<tr>
<td>c)</td>
<td>95</td>
<td>54</td>
<td>d)</td>
<td>96</td>
<td>0</td>
</tr>
<tr>
<td>e)</td>
<td>95</td>
<td>46</td>
<td>f)</td>
<td>96</td>
<td>73</td>
</tr>
<tr>
<td>g)</td>
<td>95</td>
<td>29</td>
<td>h)</td>
<td>96</td>
<td>75</td>
</tr>
</tbody>
</table>

ADE and the numerical simulation. Model 13 (fracture pattern: FS.4) shows the best fit for CTRW. Even though the ADE already provides a good simulation, the CTRW creates an even better fit. FC.2 and FS.4 are both models that have many fractures equally distributed over the reservoir.

The worst fit between the numerical model and the ADE is made for model 95 (LM.2). This model is one of the longer models. The CTRW it better capable of capturing the behaviour. CTRW has the most problems with model 50 (FO.1) and ADE is also not capable of capturing the behaviour. FO.1 only consists of one horizontal fracture. Since there is only one fracture, not enough fluid can flow through this single fracture to cool down the outlet before the cold front through the matrix arrives. The arrival of the cold front can be seen in the change of the angle of the breakthrough curve and a sudden decrease in temperature. It is very difficult for both the CTRW and the ADE to describe this behaviour, if not impossible.

The CTRW provides a better overall fit and is slightly better at describing the LT\textsubscript{10%} and the LT\textsubscript{30%}. However the CTRW needs multiple parameters to find a correct solution and it is difficult to relate them to a subsurface reservoir. The CTRW is developed for sediment transport that needs a good description of the tailing and the CTRW shows to be very useful to also capture the thermal tailing. However the CTRW is not significantly better at simulating the events that are important for geothermal energy production, such as the thermal breakthrough and the lifetime.

Describing Different Fracture Patterns with ADE

Figure 3.5a shows the fracture models that can or cannot be represented by the ADE. A small error indicates a good fit with the ADE and this good fit is found for fracture patterns that all have multiple fractures spread out over the full width of the system (FS.1, FS.4, FC case and BS.5). Model FO.3 also has a smaller error with the ADE, however this fracture pattern consists of only one vertical fracture that has minimal effect on the heat production. This numerical model can be seen as a homogeneous reservoir. LM.1 can also be represented by the ADE, however this is a longer model and will be discussed later.

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Figure 3.6: Best and Worst cases for using the ADE and the CTRW. a) Best ADE model 17 (FC.2), b) Worst ADE model 95 (LM.2), c) Best CTRW model 13 (FS.4), d) Worst CTRW model 50 (FO.1) see for the models table 3.3.
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Figure 3.7: The temperature fields for different inlet velocities and matrix permeabilities in 6 fracture models. a-d) 4 different fracture models with a constant inlet velocity of \( q = 4 \times 10^{-5} \) m/s. e-f) Fracture pattern DF.2 with two different inlet velocities. The two figures on top of each other both show the time for the same amount of produced volume. g-h) Fracture pattern FS.3 with two different inlet velocities. The two figures on top of each other both show the time for the same amount of produced volume.
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It is clear that the ADE is not capable of representing heat transfer in fractured models of which the fractures are clustered and are not evenly spread over the full reservoir (FS.3, LM.2, BS.1 to 4 and DF.1 to 3). The cold fluid that travels through the fractures, cools down the surrounding matrix resulting in a retardation of the heat velocity. When the fractures are positioned in close distance from each other, their area of influence overlap and since a matrix can only be cooled down once, the cold fluid can travel further, resulting in earlier breakthrough.

Models LM.1 and LM.2 are also interesting. Both have the same number of fractures and the same fracture density. Still, LM.1 can be described with the ADE and LM.2 cannot be described with ADE and has highly Non-Fourier behaviour. The difference between those models is the repetition of model FS.3. Model LM.1 repeats model FS.3 in series and LM.2 consists of a parallel repetition of FS.3. The parallel repetition shows the exact same behaviour of model FS.3 since the injected fluid travels over the same distance. Repeating the FS.3 in series makes the heat front experience some fracture heterogeneity several times, resulting in a Fourier-like transport.

The velocity of the injected fluid also influences the ability of the ADE to fit to the breakthrough curve of a fractured reservoir. When the injected velocity is high, there is less time to cool down the surrounding matrix with diffusion and dispersion. Figures 3.7.e-h show the cooling of two different numerical models with different inlet velocities. The models show the same produced amount of fluid and they clearly show that a lower inlet velocity causes the matrix to cool down earlier creating Fourier-like behaviour.

Figure 3.5.a also shows a very high error for the models with a low Peclet number of 2 and 0.8, which is in contradiction with the statements above. This error is not caused by the fracture flow, but by the boundary condition. The outer boundary conditions of the analytical solution assumes that at an infinite distance the temperature is $T_{in}$. For a low velocity this distance is no longer infinite and the boundary effect can be noted in the numerical result. The reason that these models are taken into account is that the error is visible at the tailing of the breakthrough curve and not at the breakthrough or the lifetime temperature. Figures 3.5.c,e and g show the small relative error at $LT_{0.1\%}$, $LT_{10\%}$ and $LT_{30\%}$ for the numerical simulations with low Peclet numbers.

From these observations I conclude that the ability of the ADE to simulate heat transfer in fractured media is dependent of the development of the cold water front. In fractured media there will be at least two cold water fronts, one travelling through the fractures and one through the matrix and each travelling with its own velocity. 'Non-Fourier' behaviour occurs when the difference in velocity between the two fronts is large. This behaviour occurs when there is a single fracture or if the fractures are close to each other and do not cover the full reservoir. However, when the fluid through the fracture is able to fully cool down the outlet before the second front arrives, the behaviour of the breakthrough curve is Fourier-like.
Figure 3.8: The influence of fracture patterns parameters on the absolute error and the relative error at LT$_{10\%}$, a) absolute error and b) relative error at LT$_{10\%}$ against $A_d$ and $A_b$, c) absolute error and d) relative error at LT$_{10\%}$ against $A_s$ and $A_c$, d) absolute and 3) relative error at LT$_{10\%}$ for the $A_{\text{infl}}$ at $t_{\text{av}}$
3.4. RESULTS

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Table 3.8: Correlation between fracture pattern parameters and the global error and relative error at LT\textsubscript{10%}

<table>
<thead>
<tr>
<th>Fracture Pattern Parameter</th>
<th>Correlation error ADE</th>
<th>relative error LT\textsubscript{10%} (\lambda\text{dis}_{pe=8})</th>
<th>(\lambda\text{dis}_{pe=75})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average density</td>
<td>-0.38</td>
<td>0.18</td>
<td>-0.01</td>
</tr>
<tr>
<td>Average Block size</td>
<td>-0.34</td>
<td>-0.08</td>
<td>-0.12</td>
</tr>
<tr>
<td>Average Spacing</td>
<td>0.10</td>
<td>-0.27</td>
<td>-0.05</td>
</tr>
<tr>
<td>Average Connectivity</td>
<td>0.03</td>
<td>-0.18</td>
<td>-0.33</td>
</tr>
<tr>
<td>Average Area of Influence</td>
<td>-0.63</td>
<td>0.01</td>
<td>-0.25</td>
</tr>
</tbody>
</table>

Fracture Pattern Parameters and the Absolute and Relative Errors

In figure 3.8 the absolute error between the ADE and the numerical simulation and the relative error at the LT\textsubscript{10%} are plotted against the fracture pattern parameters (table 3.6). Only the numerical simulations of the first part are shown to represent all the fracture patterns equally. Table 3.8 shows the correlation values for the five fracture pattern parameters and the errors. A positive correlation value indicates a positive trend between the two parameters and a negative correlation indicates a negative trend. A correlation of 1 indicates a totally linear relation and a correlation of 0 indicates that there is no relation.

The absolute error and the area of influence have a clear negative relation. A small area of influence corresponds to a large error between the ADE and the numerical simulation. This trend is in line with the conclusions that are made above. A smaller but still visible trend can be observed between the absolute error and the average density and the average block sizes. These two trends are also negative and correspond to the trend that is found between the area of influence and the error. A smaller block size means that the fractures are placed in each others area of influence and will cause the cold front to travel faster causing earlier breakthrough. This effect is caused by the velocity, \(v_h\) that is less retarded.

A small fracture average density means that the cold fluid can travel through less number of fractures. As a result, the outlet is not cooled down before the cold front through the matrix arrives, causing Non-Fourier behaviour.

The average connectivity and the average spacing that are calculated with equations 3.30 and 3.29 seem to have no influence on the error. However the way the average spacing is calculated, based on Wu and Pollard (1992) can only calculate an average value of the full model and does not account for the forming of clusters, which are very important in determining if the heat transport behaviour will be Fourier-like or not. For example, FS.3 has a very small error and can be described by the ADE and FS.1 is highly Non-Fourier-like with a large error. Both models do have the same average
Our finding that connectivity has no effect on the ability of the ADE to simulate heat transfer in a fractured reservoir is in contrast with the findings of Geiger and Emmanuel (2010) who indicated connectivity as the main influencer of Fourier-like behaviour for heat transport in a fractured reservoir. The model that the authors used in their research did have bad connectivity, however it also consisted of unequally distributed fractures. In that model, the Non-Fourier-like behaviour is caused by a small area of influence due to the unevenly distribution of the fractures. Large parts of the reservoir were not covered with fractures, while other parts consisted of a lot of fractures, much like the models in case 5. For solute transport, Matthäi and Belayneh (2004) also found that connectivity is less important due to the strong coupling between matrix and fractures. The correlation between the error at \( LT_{10\%} \) is minimal for all the fracture pattern parameters and is thus not discussed.

**Conclusion Simulating Fractured Reservoirs with ADE**

I conclude that the ADE can be used to describe heat transport in fractured reservoirs, however, there are a few restrictions. The area of influence of the fracture pattern should cover the full width of the reservoir such that it can cool down the matrix. The cooling of the matrix prevents the occurrence of two or multiple thermal fronts. The behaviour of the breakthrough curve becomes highly Non-Fourier-like if the outlet is not fully cooled down before the cold front arrives through the matrix. The size of the area of influence depends on the velocity, i.e. a high velocity results in a smaller area of influence compared to the area of influence of a low velocity.

### 3.4.3 Apparent Thermal Dispersion

As stated in section 3.2.2 there is an active discussion about the relevance and the description of the thermal dispersion. In this section three variables will be discussed and their influence on the apparent thermal dispersion. The first variable is the fracture pattern parameter determined in section 3.2.5. The second variable is the Peclet number and the third variable is the fracture-matrix permeability ratio.

**Part 1: Fracture Pattern Parameters and Peclet number**

Figure 3.9 shows the fracture pattern parameters and the apparent thermal dispersion from the numerical simulations in the first part. Each model number shows two values, red indicates the results of the numerical simulation with a low inlet velocity and blue indicates the results of the simulation with the same fracture model but with a higher inlet velocity. The model number of the numerical simulations with a high inlet velocity
can be found by adding 48 to the corresponding model number at the x-axis in the figure.

An active discussion about thermal dispersion is the relevance of thermal dispersion. Zeng-Guang et al. (1991) already concluded that heterogeneities could cause a several orders of magnitude increase of the thermal dispersion and figure 3.9 shows that the apparent thermal dispersion in a fractured system is about 3 orders of magnitude larger than the initial value in table 3.2. The apparent thermal dispersion is even bigger than the equivalent thermal conductivity \( \lambda_{eq} \) and leads to a conclusion that the apparent thermal dispersion is of great relevance in fractured media.

The second discussion concerning thermal dispersion concerns the relation between thermal dispersion and the Peclet number. Figure 3.9.a shows that Peclet and the fracture pattern greatly influence the apparent thermal dispersion. The Peclet number influences first of all the amplitude of the apparent thermal dispersion, the dispersion is bigger for a higher Peclet number and the same model parameters. Thereby, the Peclet number also influences the response of the apparent thermal dispersion to the subsurface properties. Cases FS and FC show this clearly. The apparent thermal dispersion has the same value for models FS.1, FS.2 and FS.3 for an inlet velocity of \( 4 \times 10^{-5} \) (m/s) however, the dispersion value changes for the models when the inlet velocity is decreased to \( 4 \times 10^{-6} \) (m/s) resulting in different apparent thermal dispersion values. These variations show the dependency of thermal dispersion on both the velocity and the subsurface properties, in this case the fracture pattern.

The apparent thermal dispersion is equal for the models with the same fracture pattern and velocity and a varying permeability and shows the minimal influence of the matrix permeability for these models.

Figures 3.9.a-e also show the fracture pattern parameters for each model. The correlation between the apparent thermal dispersion and the the fracture pattern parameters is shown in table 3.8. Since the apparent thermal dispersion changes for the different values of Peclet, the correlation is calculated separately for the models with a different inlet velocity. The largest correlation is found for \( A_c \), however, there are only a few values for this parameter because not all the models have connecting fractures.

Figure 3.9.f plots the average area of influence, \( A_a \), against the apparent thermal dispersion on a logarithmic scale. The average area of influence shows the fraction of the area that is influenced by the fracture flow. In the figure, the different fracture cases and inlet velocities are identified with different symbols and colors, respectively. A clear relation can be noted between the area of influence and the thermal dispersion for the two values of Peclet. Only the block size cases deviate from the trend for an inlet velocity of \( 4 \times 10^{-5} \) m/s. The deviation may be caused by the larger area that is covered by fractures in the BS case. The fractures in the BS case stretch out over a longer area than the other fracture patterns.

The apparent thermal dispersion increases for the longer models, which is in line with
the findings in Saeid et al. (2014). However, there is only one horizontally longer model and that is not enough to draw conclusions from and more research should be conducted into this topic.

Part 2: Peclet number and Fracture-Matrix Permeability Ratio

The models that are made in part 2 (table 3.4) are used to examine the influence of Peclet and the fracture-matrix permeability ratio on the apparent thermal dispersion (figure 3.10.a). The models with a fracture aperture of 0.1 mm and a permeability ratio of $8 \times 10^2$ show a very different behaviour compared to the models with an higher permeability ratio and a larger aperture.

The reaction of the apparent thermal dispersion to Peclet is the same for all the different models and fracture-matrix permeability ratios for the low values of Peclet ($Pe < 1$). However, for an increasing $Pe$, the permeability ratio significantly influences the apparent thermal dispersion. The apparent thermal dispersion of the numerical simulations with a fracture aperture of 1 mm and a permeability ratio larger than $8 \times 10^2$, increases rapidly for higher Peclet numbers. The apparent thermal dispersion of the numerical simulations that have a fracture aperture of 0.1 mm and a permeability ratio of $8 \times 10^2$, increases less rapidly for higher Peclet numbers.

The apparent thermal dispersion slightly increases for smaller becoming $Pe$ if the $Pe$ is smaller than 1. This behaviour is also observed by Rau et al. (2012) and Zeng-Guang et al. (1991). It is explained as an effect of the high conductivity ratio between the solid and the fluid.

For the full $Pe$ range, the behaviour of the apparent thermal dispersion for models with permeability ratios of $8 \times 10^4$ and $8 \times 10^6$ are exactly the same. This conclusion is also made above based on figure 3.9. The behaviour of the apparent thermal dispersion against Peclet for the numerical simulations with a permeability ratio of $8 \times 10^3$ corresponds to the behaviour of the models with a permeability ratio of $8 \times 10^4$, however it is not exactly the same.

Figures 3.10.b to 3.10.e show the values of the thermal dispersion parameters (section 3.2.2) against Peclet. All four thermal dispersion parameters show a decreasing value for increasing Peclet, for the numerical models with a low fracture-matrix permeability ratio of $8 \times 10^2$.

The thermal dispersion parameters of the numerical models with a higher permeability ratio, do not show a constant value for any of the proposed relationships, indicating that non of the relations can describe the full behaviour of thermal dispersion against Peclet. For the intermediate Peclet numbers ($1 < Pe < 10$) the parameter of Sauty et al. (1982) (figure 3.10.b) has a constant value, indicating a linear relation in this range.

The parameter from Lu et al. (2009) (figure 3.10.c) is slightly increasing. The thermal dispersion parameter from Metzger et al. (2004) (figure 3.10.c) and Rau et al. (2012) (figure 3.10.b) both show a decreasing value. For the high Peclet numbers (Pe> 10), the
Figure 3.9: The apparent thermal dispersion for each model compared to the fracture parameters: a) Average Density, b) Average Spacing, c) Average Block Size, d) Average Connectivity e) 1/average area of influence for \( t_{av} \) f) the thermal dispersion against the average area of influence, the different fracture cases ans inlet velocity are indicated.
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Figure 3.10: a) Thermal Dispersion against Peclet for different fracture patterns and permeability ratio’s, b) Thermal dispersion parameters $\alpha_L$ (Sauty et al., 1982), c) thermal dispersion parameter $k$ (Lu et al., 2009), d) thermal dispersion parameter $\gamma$ (Metzger et al., 2004), e) thermal dispersion parameter $\beta$ (Rau et al., 2012)
dispersion model of Sauty et al. (1982), and Lu et al. (2009) show a positive relation with Pe and Rau et al. (2012) shows a negative relation with Pe. The thermal dispersion parameter $\gamma$ (figure 3.10d) shows that the Peclet number and permeability ratios aren’t the only parameters influencing the behaviour of the thermal dispersion parameters, the fracture pattern also determines the reaction of the thermal dispersion parameters to Peclet. The slope of the thermal dispersion parameter $\gamma$ is different for model BS.4 compared to models FC.1 and FC.5. The thermal dispersion coefficients of models FC.2 and FC.5 both show a decreasing behaviour for $Pe < 10$ and an increasing behaviour for $Pe > 10$, the parameter for BS.4 shows a constant declining behaviour for the full range of Pe.

The conclusion from the observations above is that the relation between Pe and the thermal dispersion is not the same for all Peclet values, fracture patterns and permeability ratios. To examine the influence of Pe on the apparent thermal dispersion the idea of Detwiler et al. (2000) is used on thermal transport. Detwiler et al. (2000) found that for small Pe numbers, the solute dispersion is independent of Peclet. In heat transfer a small negative relation is visible between Pe and the apparent thermal dispersion for $Pe < 1$. For intermediate values of $Pe$ Detwiler et al. (2000) indicated a linear relation between Peclet and the solute dispersion. This relation can also be proposed for heat transfer for $1 < Pe < 10$ (apparent $\lambda_{dis} \propto Pe$) based on figure 3.10b. For solute transport Detwiler et al. (2000) proposed a square Peclet relationship for larger values of Pe. This relation is implemented by Rau et al. (2012) and is shown in figure 3.10c. Metzger et al. (2004) also proposes a power law, however with an exponent of 1.59 (figure 3.10d). The thermal dispersion parameter $k$ has a positive relation for $Pe > 10$ with an exponent of 1.59 in the power law and $\beta$ has a negative relation with an exponent of 2. The right exponent to get a constant thermal dispersion parameter would be some what in the middle. That is why I propose a power law for the higher regions of Pe (apparent $\lambda_{dis} \propto Pe^n$). The parameter $n$ would be dependent on the fracture pattern and solute properties. In the literature, only the thermal dispersion coefficients are dependent of the subsurface properties Lu et al. (2009), Rau et al. (2012), Sauty et al. (1982), Zeng-Guang et al. (1991) and not the parameter $n$, however, Green et al. (1964) and later Metzger et al. (2004) also indicated that the power law should be determined empirically.

A note should be made that the proposed regimes are made for the models with a permeability ratio between $8 \times 10^3$ and $8 \times 10^6$. To construct a relation between Pe and the apparent thermal dispersion for lower permeability ratios, more research should be conducted.

**Conclusion Apparent Thermal Dispersion**

The apparent thermal dispersion can be characterized by the Peclet number of the system in two ways. First of all, the area of influence is dependent of the Peclet number and the thermal dispersion responses to a change of the area of influence. Second, the Peclet number indicates how the apparent thermal dispersion response to Peclet. The
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thermal dispersion is minimally depended of Peclet for small values of Peclet (Pe< 1). For intermediate values of Peclet, the relationship is linear (< 1Pe< 10), and for large values of Pe (Pe>10), the relation between the thermal dispersion and Peclet can be described with a power law. The apparent thermal dispersion is also influenced by the fracture-matrix permeability ratio and fracture aperture.

3.4.4 Breakthrough, Cool down and Lifetime

In this section the effect of the fracture patterns on the breakthrough time (t0.1%), the cool down time (t97%) and the lifetime (t10%) is discussed. The lifetime at (t30%) is not discussed because the LT10% and LT30% show a very similar behaviour. Figure 3.11 shows the various times, expressed in produced pore volume for each model for different scenarios. Figure 3.11a shows the absolute pore volume and figure 3.11b the pore volume that is divided by the total pore volume of the model. Figure 3.11a shows the fluctuation of the breakthrough better and the figure 3.11b shows the changes in the cool down time better.

As indicated before the Peclet number influences the behaviour of system. In a homogeneous system, a low Peclet number describes a system with a large diffusion and this results in an earlier breakthrough compared to a system with a higher Peclet number. However, in a fractured media (figure 3.11), the numerical simulations with a high Peclet number have an earlier breakthrough. Only models BS.5, BS.6, the first two DF models, the F.O models and the high permeability model of model FS.3 still show an earlier breakthrough for lower Peclet systems. All these models have a large area that is not covered by fractures.

More volume can be produced before the matrix is fully cooled down of systems with a high Peclet number. The time between the breakthrough and the cooling down time is larger for high Peclet systems compared to low Peclet systems and indicates a larger tailing. Since it is difficult for the ADE to describe both earlier breakthrough and long tailing, this supports the previous conclusion that models with a higher velocity create more Non-Fourier like behaviour of the heat transfer.

The t0.1% is influenced by the permeability of the matrix in a few models. In these models, the breakthrough occurs later for the numerical simulations with a higher \( \kappa_m \). For models with higher \( \kappa_m \) values, more fluid will flow through the matrix resulting in a later breakthrough.

There is also a relation between the matrix permeability and the cool down time. The main trend is that a higher permeability creates a shorter cool down time as result of more fluid flowing through the matrix and less through the fractures. However, there are also models where a higher permeability results in later cool down time (FS.2, FC.4 and BS.3). This is a result of more fluid flowing through the fractures instead of the matrix. A reason for this behaviour might be that the fluid can travel easier to the fractures due to the higher permeability of the matrix.
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The behaviour of the life time ($LT_{10\%}$) corresponds to the behaviour of the breakthrough ($LT_{0.1\%}$). In all the models, less fluid is produced before reaching the lifetime temperature in systems with a high Peclet number.

Figure 3.12a shows the breakthrough and the area of influence for the different models. Here the trend is fairly minimal. Figure 3.12b shows the effective permeability of all the models. As expected, the fractures contribute more to the effective permeability for the systems with lower matrix permeability.

**Case 1: Orientation**

The influence of orientation is significant. The numerical model with only one horizontal fracture causes an early breakthrough. This effect is also observed by Fu and Carrigan (2014) who indicated that when a doublet is placed in-line with the fractures, the breakthrough occurs much earlier compared to a doublet that is placed perpendicular to the fractures. The vertical fracture has no influence on the heat transport and can be seen as an homogeneous model. The model with the diagonal fracture has the same fracture density as the model with one horizontal fracture, however, $\kappa_{\text{eff}}$ is much smaller (figure 3.12b) and therefore more fluid is flowing through the matrix resulting in less Non-Fourier behaviour. The area of influence is very small since there is only one fracture and this makes the heat transport difficult to be described with the ADE applied on EPM.

**Case 2: Fracture Spacing**

Fracture spacing influences the heat production and determines whether or not the system can be described as Fourier-like or not. When fractures are placed in each others area of influence, the cold front can travel further since the velocity of the cold front is less retarded by the matrix. Sudicky and Frind (1982) also observed this effect for solute transport. Figure 3.11 shows that increasing the fracture density delays the breakthrough and shortens the tailing resulting in a more Fourier-like behaviour. The $\kappa_{\text{eff}}$ becomes smaller for closer placed fractures (figure 3.12). This is in contrast with the findings of Matthäi and Belayneh (2004) who found an increasing effective permeability for a fractured reservoir with smaller spacing. However, the fractured reservoirs from Matthäi and Belayneh (2004) had fractures that were all placed at different distance from the boundary. In the fracture spacing case in this thesis the fractures are all placed on the same distance from the boundary. I will get back to this inconsistency in case 4.
3.4. RESULTS

CHAPTER 3. INFLUENCE OF FRACTURES

Case 3: Fracture Connectivity

The spacing also influences the breakthrough of the connectivity cases (figure 3.11). The only parameter that changes between models FC.3 and FC.5 and the models FC.4 and FC.6 is the spacing between the clusters. In FC.3 and FC.4 the blocks are further apart from each other and closer to the boundary. There is also a small change in breakthrough between the fully open model (FC.1) and the other models of case FC. In the fully open model the vertical fractures have little contribution to the fluid flow, while in model FC.2 due to the higher connectivity, more fluid flows through the fractures. The effective permeability also responds to the increase in connectivity between FC.1 and the rest of the models (figure 3.12b). The effect of connection on the breakthrough and the effective permeability is interesting since the effect on the apparent thermal dispersion and the error is minimal. It seems that the connectivity only influences the breakthrough and has no effect on the further behaviour of the breakthrough curve. More research could be conducted into this topic.

Case 4: Block sizes

One of the main parameters controlling the breakthrough and cool down time is the vertical spacing between the fractures. When there are no vertical fractures, the effective permeability decreases. The change of the effective permeability for different block sizes is minimal. Only the presence of the vertical fracture influence the permeability.

The size of the blocks has a significant effect on the breakthrough time. A smaller block size indicates an earlier breakthrough time. This effect is also found by [Juliusson and Horne (2010)]. They studied the boundary effect of an impermeable matrix on the arriving time of fluid and heat and they found that an increasing block size also increases the arrival time of the cold injected fluid. However, according to [Juliusson and Horne (2010)] there is a limit for this effect. [Roubinet et al. (2010)] found this limit as well for solute transport. This limit might be connected to the area of influence.

In contrast with my findings in case 2, the effective permeability becomes larger for a decrease in fracture spacing. The small change can be seen best for the models with no vertical fractures. This effect is in accordance with the findings of [Matthäi and Belayneh (2004)], because the fracture placing in the block size case corresponds with the fracture placing of [Matthäi and Belayneh (2004)]. The diagonal alignment of the fractures creates a different pressure build up compared to vertical aligned fractures. When the spacing between diagonal aligned fractures is larger, the pressure gradient is also bigger, because the distance between a fracture and a horizontal boundary is at its maximum. A larger pressure gradient gives a smaller permeability according to equation 3.10. For vertical aligned fractures the spacing between the boundaries is at its maximum for small fracture spacing, because then the spacing between the outer fracture and the boundary is at its maximum creating a large pressure gradient and a small $\kappa_{\text{eff}}$. 

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3.5 Discussion

This thesis studies the impact of fractures on heat production, however the fracture outlines that are constructed here are highly idealized. The aperture of the fractures is equal over the full reservoir. In a real aquifer, fracture aperture sizes can change over the field due to different chemical, mechanical and physical processes. Thereby, not only fractures cause heterogeneities, different deposits, clogging or cementation can change the permeability field as well (Geiger and Emmanuel, 2010).

Case 5: Diagonal models

The numerical simulations in this case show that locating the fractures only around the producer, increases the breakthrough time since the fluid will have to travel through the matrix to reach the fractures. The location of the intersection mainly influences the cooldown time of the system.

Case 6: Longer Models

Model LM.2 has the same profile as FS.3 since the fluid travels over the same distance through the same fracture pattern. The in series repeated model (LM.1) has as expected a later breakthrough since the model is longer.

Figure 3.11: The produced pore volume at BT and at CD for high and low inlet velocity. a) The absolute produced pore volume b) The sweep efficiency, produced pore volume/total pore volume model
I found that the apparent thermal dispersion and Fourier-like behaviour of the fractured numerical system, is dependent of the area of influence. The $A_a$ is only calculated for a fracture aperture of 1 mm. Further research could look into variable aperture sizes and its influence on apparent thermal dispersion.

The CTRW showed to be successful to describe heat transport in fractured media however the method uses five parameters to create a fit to the breakthrough. These parameters are difficult to relate to the real field, such as the most prominent parameter $\beta$ (Ciriello et al., 2013) or $t_1$ and $t_2$. Due to the various options in creating an optimal fit, it is also difficult to determine when a fit is optimal.

The study is also limited due to some of the design choices that are made. None of the fracture patterns have fractures that connect the left boundary to the right boundary. When the fractures reach from the left to the right boundary some fluid will only travel through the fractures. If less fluid would travel through the matrix, the difference between the heat velocity of the fluid through the matrix and the heat velocity of the fluid through the fractures would increase, resulting in non-Fourier-like behaviour. However, for a longer reservoir, the fluid through the fractures has longer to decrease the temperature at the outlet. If the cold front through the fractures is able to fully cool down the outlet, it will result in more Fourier-like behaviour. Also neglecting the changes of viscosity and density due to temperature changes, influences the outcomes of this study.

A limitation of the implementation of this study is the knowledge of the fracture maps in the subsurface. It is difficult to capture fractures from cores and the translation from outcrops to the subsurface also has it limits. These limitations make it difficult to predict the spacing and the orientation of the fractures to calculate the area of influence.
3.6. CONCLUSION

Thereby, this study is conducted in a 2D field and it would be interesting to see how the area of influence develops in a 3D field.

The tree regimes that are constructed for thermal dispersion are based on 5 data points and 3 fracture patterns. More research should be conducted to test the viability of the three regimes. Thereby, the response of the thermal dispersion to Peclet changes with different fracture apertures so further research should be conducted into the effects of the fracture aperture. Further research could also look into the effect the fracture-matrix permeability ratio.

3.6 Conclusion

In this thesis the influence of fractures on heat production in fractured reservoirs is studied. Multiple numerical stimulations are conducted using lower dimensional line elements as fractures. The fracture patterns are designed such that the influence of orientation, fracture spacing, fracture connectivity, fracture density, and block sizes could be studied.

The Advective Diffusivity Equation (ADE) is fitted to the breakthrough curves of the numerical simulations by adjusting the apparent thermal dispersion. When the ADE is not able to capture the emergent behaviour, the Continuous Time Random Walk framework is used to simulate the Non-Fourier-like behaviour.

The CTRW framework is successful in simulating the full breakthrough curve, however it shows limitations in capturing the breakthrough of the cold fluid. The economic viability of a geothermal reservoir is greatly dependent on the life time of a geothermal reservoir and the CTRW is able to predict this moment quite accurate. The ADE shows to be less successful compared to the CTRW in capturing the full behaviour of the breakthrough curve, however the ADE is better in estimating the breakthrough time. The life time is estimated better by the CTRW however the ADE also shows a good estimation.

From my research I conclude that the ADE, applied to an EPM, can be used to describe heat transfer in fractured reservoirs however there are some limitations. The ADE is not able to capture the behaviour of a fractured reservoir when the area of influence of the fractures does not cover the full width of the reservoir. For the fractured systems that have an area of influence that does not covered the full width of the model, two cold fronts evolve, one through the fractures and one through the matrix. If the cold front of the matrix arrives at the outlet before the cold fluid through the fractures has cooled down the outlet, a highly Non-Fourier behaviour of the breakthrough will occur.

When the fractures are placed in each others area of influence the cold injected fluid can travel further because it is less retarded by the matrix, creating an even earlier breakthrough. This effect is only visible when the area of influence of the fractures does not cover the full width of the reservoir.
To fit the ADE, solved for an effective porous media, the apparent thermal dispersion needs to be adjusted. I found that the area of influence also influences the apparent thermal dispersion. A negative relation could be constructed between the two parameters.

The discussion about thermal dispersion and its dependency on Peclet is also addressed in this thesis. Different relations between Peclet and the apparent thermal dispersion are studied. I found that the three regimes that [Detwiler et al. (2000)] constructed for solute longitudinal dispersion can also be constructed for the apparent thermal dispersion. For values of Pe<1, the apparent thermal dispersion has a very small negative to zero relation with Pe. For intermediate values of Pe (1<Pe<10) Peclet is linearly related to the apparent thermal dispersion and for larger values of Peclet a power law relation can be constructed. The power law and the additional parameters are dependent on the subsurface parameters and the fracture pattern.

The three regimes can only be constructed for permeability ratio between $8 \times 10^3$ and $8 \times 10^6$. The numerical simulations that have a smaller permeability ratio respond less to an increasing Peclet number. However not enough data is collected to construct a relation.

The breakthrough time is strongly influenced by the position of the horizontal fractures. A smaller spacing between the fractures decreases the breakthrough time and the breakthrough time is increased if the orientation of the doublet is not in line with the fractures. The vertical fractures also influence the breakthrough if the fractures are connected to horizontal fractures.
Chapter 4

Implementations

This chapter shows the implementations of the study in the previous chapter. The first question that can be answered is: How do fractures influence the breakthrough and the lifetime of a geothermal reservoir? Fractures have a significant influence on the production of heat; they decrease the life time of the reservoir and increase the effective permeability. An increase of the permeability, decreases the needed pressure to produce from a reservoir, what can enhance the economic value of a geothermal reservoir.

The following aspects need to be taken into account when deciding on a location for a geothermal doublet:

**Heterogeneity**

To get an insight in the possible contribution of fractures to the heat production, it is important to know the permeability ratio \( \frac{\kappa_{\text{frac}}}{\kappa_m} \). The permeability ratio provides information about the contribution of the fractures to the flow.

**Fracture Orientation**

The fracture orientation determines the breakthrough moment significantly. A doublet that is positioned in-line with the fractures decreases the breakthrough, however it increases the effective permeability [Fu and Carrigan, 2014].

It is also important to know if the fractures only exist in one direction, or if there are perpendicular fractures as well. If the vertical fractures are connected to the horizontal fractures, they contribute to the flow path and increases the permeability. Fractures in multiple orientations will create an earlier breakthrough.

**Fracture location**

The location of the fractures will also influence the produced amount of heat. More heat can be produced if the fractures are not present in the full interval between the doublet and the injector.
Fracture Spacing
The fracture spacing is what mainly influences the breakthrough of a system. If the fractures are located in close distance of each other, they cool down the same matrix. The cold front can travel further and create an earlier breakthrough. A problem will arise if the fractures are not equally spread over the reservoir or if their area of influence does not overlap. A result of the forming of clusters, is the development of two cold fronts, one through the matrix and one through the fractures. If there are two cold fronts, the behaviour is highly non-Fourier-like and it is difficult to simulate the breakthrough with a simple Advection-Diffusivity Equation. However, if the cold fluid through the fractures is able to cool down the outlet, the behaviour is again Fourier-like.

Fluid Velocity
In a homogeneous reservoir with a low Peclet number, less hot fluid can be produced due to the diffusion of the cold fluid. In a fractured system, the models with a high Peclet number produce less hot fluid. So, increasing the fluid velocity will result in earlier breakthrough in a fractured system.

Modelling of the heat production
This study shows that thermal dispersion can not be neglected when calculating the breakthrough. The thermal dispersion is influenced by the area of influence, which can be calculated with the production rate and a fracture map. The area of influence can also give information about the behaviour of the system and if the behaviour can be described with the Advection-Diffusivity Equation. This information can be used to make the modelling of fractured reservoir easier.
Bibliography

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Nomenclature

Glossary
ADE Advection-Diffusivity Equation
BT Breakthrough
CTRW Continuous Time Random Walks
LT Life Time
RVG Roer Valley Graben
TPL Trucated power law
WNB West Netherlands Basin

Subscripts
0.1% breakthrough
10% Temperature drop of 10%
30% Temperature drop of 30%
97% Cool down
ψ CTRW parameter
abs absolute
BT fitted to the breakthrough
$c$ concentration
dis thermal dispersion
eff effective
eq equivalent
$f$ fluid phase
frac fracture
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$h$</td>
<td>heat</td>
</tr>
<tr>
<td>$i$</td>
<td>counter</td>
</tr>
<tr>
<td>$L$</td>
<td>longitudinal direction</td>
</tr>
<tr>
<td>$m$</td>
<td>matrix</td>
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<tr>
<td>model</td>
<td>solution from the ADE, ADE$_{BT}$ or CTRW</td>
</tr>
<tr>
<td>$n$</td>
<td>number</td>
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<tr>
<td>num</td>
<td>numerical solution</td>
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<td>out</td>
<td>outlet</td>
</tr>
<tr>
<td>rel</td>
<td>relative</td>
</tr>
<tr>
<td>$s$</td>
<td>solid phase</td>
</tr>
<tr>
<td>sc</td>
<td>solutes</td>
</tr>
<tr>
<td>$T$</td>
<td>transversal direction</td>
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</tbody>
</table>

**Variables**

- $\alpha$: thermal dispersion coefficient [Sauty et al., 1982]
- $\beta$: heterogeneity parameter
- $\beta$: thermal dispersion coefficient [Rau et al., 2012]
- $\epsilon$: error
- $\Gamma$: incomplete Gamma function
- $\gamma$: thermal dispersion coefficient [Metzger et al., 2004]
- $\kappa$: permeability
- $\lambda$: thermal conductivity
- $\mu$: dynamic viscosity
- $\phi$: porosity
- $\psi$: truncated power law
- $\rho$: density
- $A$: Area
- $A_a$: average area of influence
- $A_b$: average block size
- $A_c$: average connectivity
A_{\text{infl}} & \text{area of influence} \\
A_s & \text{average spacing} \\
B_i & \text{area of a block limited by at least 3 fractures} \\
B_n & \text{total amount of blocks} \\
c & \text{specific heat capacity} \\
D & \text{diffusivity} \\
d_f & \text{fracture aperture} \\
d_g & \text{characteristic length} \\
k & \text{thermal dispersion coefficient} \quad \text{(Lu et al., 2009)} \\
L & \text{length} \\
l & \text{length fracture} \\
l_0 & \text{side height of the model} \\
L_{\text{infl}} & \text{effective length of influence} \\
l_{\text{infl}} & \text{length of influence} \\
L_{\text{space}} & \text{spacing between two fractures} \\
M & \text{Memory function} \\
n_0 & \text{number of fractures} \\
n_i & \text{number of clusters} \\
n_s & \text{number of sides of the fractures} \\
P & \text{Pressure} \\
Pe & \text{Peclet number} \\
q & \text{fluid velocity} \\
R & \text{Retardation} \\
s & \text{solute} \\
T & \text{temperature} \\
t & \text{time} \\
t_1 & \text{characteristic time for transition between sites} \\
t_2 & \text{time after the system becomes Fourier-like} \\
T_{\text{in}} & \text{initial temperature}
$T_{\text{inj}}$ injected temperature
$u$ dimensional Laplace variable
$v$ effective velocity
$x$ direction
$y$ direction

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Appendices
Appendix A

All Breakthrough Curves and fitted solutions
APPENDIX A. ALL BREAKTHROUGH CURVES AND FITTED SOLUTIONS

Figure A.1: BTC figure 1-8
Figure A.2: BTC figure 9-16
Figure A.3: BTC figure 17-24
Figure A.4: BTC figure 25-32
APPENDIX A. ALL BREAKTHROUGH CURVES AND FITTED SOLUTIONS

Figure A.5: BTC figure 33-40
APPENDIX A. ALL BREAKTHROUGH CURVES AND FITTED SOLUTIONS

Figure A.6: BTC figure 41-48
Figure A.7: BTC figure 49-56
APPENDIX A. ALL BREAKTHROUGH CURVES AND FITTED SOLUTIONS

Figure A.8: BTC figure 57-64
APPENDIX A. ALL BREAKTHROUGH CURVES AND FITTED SOLUTIONS

Figure A.9: BTC figure 65-72
APPENDIX A. ALL BREAKTHROUGH CURVES AND FITTED SOLUTIONS

Figure A.10: BTC figure 73-80
Figure A.11: BTC figure 81-88
Figure A.12: BTC figure 89-96
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APPENDIX A. ALL BREAKTHROUGH CURVES AND FITTED SOLUTIONS

Figure A.14: BTC figure 109-116
Figure A.15: BTC figure 117-124
Figure A.16: BTC figure 125-132
Figure A.17: BTC figure 133-139
Appendix B

Correlations from IF

B.1 Röt Fringe Sandstone Member

B.1.1 Porosity Depth Relation

Maaijwee et al. (2012) used porosity and permeability measurements from cores from the Röt fringe sandstone member to determine the average porosity and depth relation at the different locations. Maaijwee et al. (2012) assumed a linear relation between the porosity and permeability and showed an interpretation with two linear relations and one outline, STH-01. The Triassic is found quite shallow in STH-01 and it lies left of a large fault so it is not a surprise that it is an outline.

Maaijwee et al. (2012) does not give a clear reason for the two relations however they indicate that it probably depends on the different deposition environments.
Figure B.1: Relation between the porosity and the depth of the Röt Fringe Sandstone Member (Maaijwee et al., 2012). The upper equation (equation B.2) describes the lower line and the lower equation (equation B.1) describes the upper line

\[
\text{Porosity} = -7.0402 \times 10^{-5} \times \text{Depth} + 0.2339 \quad (\text{B.1})
\]

\[
\text{Porosity} = -8.7924 \times 10^{-5} \times \text{Depth} + 0.3329 \quad (\text{B.2})
\]

In figure B.2 the relation between location and the depth-porosity relation is shown. According to Maaijwee et al. (2012), equation B.1 is related to alluvial fan deposits and equation B.2 is related to a fluvial braid plain deposits in the centre of the graben. Loveless et al. (2013) indicated that the different relation depend on differences in cementation.
B.1.2 Porosity Permeability Relation

In “het Brabant breed onderzoek” the assumption is made that the relation between porosity and permeability can be approached with an exponential relation. The figure below gives the relations that was found in Brabant. An observation that can be made is that the two indicated relations between depth and porosity are not visible any more. Again Maaijwee et al. (2012) indicates two different relations, now based on the porosity. STH-01 is again an outline.

For porosity > 0.11

\[ \text{Permeability} = e^{0.4091+39.446 \times \text{porosity}} \]  \hspace{1cm} (B.3)

For porosity < 0.11

\[ \text{Permeability} = e^{-16.059+186.51 \times \text{porosity}} \]  \hspace{1cm} (B.4)

The location of the two relations are indicated in figure 2.3.
Figure B.3: Relation between the porosity and the permeability of the Röt Fringe Sandstone Member (Maaijwee et al., 2012)

Figure B.4: Location of the measured cores. The two different relations are indicated. The upper relation, equation B.3 with blue stars, the lower, equation B.4 with red stars.
B.2 Lower Germanic Triassic Group and Basal Solling Sandstone

Maaijwee et al. (2012) combined the information of multiple formations to construct the relation between depth, porosity and permeability for the Lower Germanic Triassic Group (LGTG) and the Basal Solling Sandstone (BSS). Adding the different layers together creates a large inaccuracy, however Maaijwee et al. (2012) still added the different layers together since there was not enough information for each individual layer.

B.2.1 Porosity Depth Relation

For the Lower Germanic Triassic Group and the Basal Solling Sandstone, Maaijwee et al. (2012) constructed the relations for the depth and the porosity.

\[
\text{Porosity} = -3.8318 \times 10^{-5} \times \text{Depth} + 0.1844 \tag{B.5}
\]

Figure B.5: Relation between the porosity and the depth of the Lower Germanic Triassic Group and Basal Solling Sandstone (Maaijwee et al., 2012). The upper equation (equation B.6) describes the lower line and the lower equation (equation B.5) describes the upper line.
B.2.2 Porosity Permeability Relation

The relation between the porosity and permeability is also divided into two sections.

For porosity > 0.1

\[ \text{Permeability} = e^{-2.1070 + 51.909 \times \text{Porosity}} \]  \hspace{1cm} (B.7)

For porosity < 0.1

\[ \text{Permeability} = e^{-27.750 + 312.72 \times \text{Porosity}} \]  \hspace{1cm} (B.8)

Figure B.6: Location of the two relations of the Lower Germanic Triassic Group. The triangles are described by equation [B.5] and the squares show equation [B.6]
Figure B.7: Relation between the porosity and the permeability of the Lower Germanic Triassic Group and Basal Solling Sandstone (Maaijwee et al., 2012)

Figure B.8: Location of the measured cores. The two different relations are indicated. The upper relation with yellow stars showing equation B.7 and the lower one with blue stars following equation B.8
B.3 Geothermal Gradient

The Geothermal gradient is also determined in “het Brabant Breed onderzoek” (Maaijwee et al., 2012). The bottom bottom hole temperature was used from 20 wells (Maaijwee et al., 2012) to construct a relation. KWK-01 and WWK-01 were not used to calculate the geothermal gradient because they were conflicting. Since using bottom hole temperatures is not very reliable, corrections were used. The gradient came to:

\[ \text{Temperature} = 4.8859 + 0.0369 \times z \]  \hspace{1cm} (B.9)

Parameter T is the temperature in degrees Celcius and z is depth in m and is valid for a depth range between 1153.2 and 3241.9 TVD below Surface in the Roer Valley Graben. The constructed gradient is a higher gradient than that is be found in the rest of the Netherlands (Maaijwee et al., 2012). The uncertainty is shown in figure B.9.
Appendix C

Overview Triassic depositions in the Netherlands
APPENDIX C. OVERVIEW TRIASSIC DEPOSITIONS IN THE NETHERLANDS

Figure C.1: Triassic deposition in the Netherlands, (Bachmann et al., 2010)
Appendix D

Numerical Tolerance

The accuracy of a numerical calculation is dependent on the absolute and the relative error. In the numerical simulation the errors are influenced by the relative and absolute tolerance. A smaller tolerance indicates a more accurate solution. However, a smaller tolerance also indicates a longer computing time of the solution. The solver uses the tolerances to find an accurate step size to satisfy the error restrictions. The relative tolerance is a dimensionless number that controls the error of all the dependent variables. The absolute tolerance determines the absolute error and is given in the same units as the dependent values to which it applies.

Figure D.1 shows the analytical solution with four numerical solutions of the breakthrough curve all with different tolerances. The figure shows that the numerical model with a relative and absolute tolerance of $10^{-6}$ creates an accurate solution. Figure b is a zoomed in image of figure D.1.
APPENDIX D. NUMERICAL TOLERANCE

(a) Breakthrough Curve analytical and numerical solution

(b) Zoomed in on figure a

Figure D.1: Breakthrough curve of the same numerical model with different tolerances
R indicates the relative tolerance, A the absolute tolerance
Appendix E

Change Apparent dispersion or Velocity

In this thesis only the apparent dispersion is adjusted to find a fit between the numerical simulation and the ADE. Fractures create an early breakthrough and cause long tailing (Dentz et al. 2004). In the ADE equation the velocity describes the moving of the thermal front and the diffusion covers the spreading of the mass around the thermal front. The overall velocity of the system is not changed, however the spreading of the cold fluid is changed significantly because some of the cold fluid travels through the fractures.

The following figures show how a figure responds to a higher velocity and to a higher dispersion.
APPENDIX E. CHANGE APPARENT DISPERSION OR VELOCITY

Figure E.1: BTC of model FC.6 with $v_h = 6.2 \times 10^{-6}$ m/s and $D = 7.7225 \times 10^{-7}$ m$^2$/s

Figure E.2: BTC of model FC.6b with $v_h = 1 \times 10^{-5}$ m/s and $D = 7.7225 \times 10^{-7}$ m$^2$/s

Figure E.3: BTC of model FC.6 with $v_h = 6.2 \times 10^{-6}$ m/s and $D = 5 \times 10^{-6}$ m$^2$/s