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Continuous Hybrid Cooling

Subsurface Heat Modelling to Establish Feasibility of Absorption Cooling in Oman

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I. INFORMATION

Continuous Hybrid Cooling
Subsurface Heat Modelling to Establish Feasibility of Absorption Cooling in Oman

Research Question:

Is absorption cooling possible for the climatic conditions in Oman?

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II. STATEMENT OF ORIGINALITY

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Title report / thesis:

Continuous Hybrid Cooling: Subsurface Heat Modelling to Establish Feasibility of Absorption Cooling in Oman

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- where I used the ideas of other writers, I acknowledge the source in every instance,
- where I used any diagrams or visuals, I acknowledged the source in every instance,
- this thesis (or part of it) was not and will not be submitted as assessed work in any other academic course.

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III. SUMMARY

In a cooperation between The Research Council of Oman, GFZ Potsdam, TU Berlin and the German University of Technology in Oman a pilot project was set up to investigate a Continuous Hybrid Cooling system. This is an alternative air-conditioning system that runs entirely on renewable energy sources.

In Oman and other regions with a hot climate air conditioning systems are one of the biggest consumers of electrical power. In Oman 97.5% of electricity is generated by natural gas combustion. In order to reach the goal of low-carbon consumption, a pilot project with absorption cooling that does not rely on fossil energy, could deliver a major contribution. Absorption cooling systems utilize thermal energy to produce chill. Their coefficient of performance depends strongly on the ability to reject heat. The ambient air temperature of Oman is too high to efficiently reject the heat to. The subsurface has a more stable and cooler climate. Subsurface heat rejection is therefore potentially an option.

Subsurface heat streams are simulated in different modelling configurations to establish feasibility of absorption cooling in Oman. The simulation is built in COMSOL Multiphysics and expands on previous models. The coupling techniques of 1D, 2D and 3D domains are employed as tools to visualize behavior of subsurface heat streams. The main research questions whether absorption cooling is possible for the climatic conditions of Oman is answered by first establishing the variables. According to the model target heat rejection of 1,500 kW can be achieved, this does remain dependent on the configuration of the system (borehole depth, volume flow through the borehole etc.). The maximum obtainable heat rejection is dependent on the chosen parameters. From the model runs it appears that an increase of depth of the borehole results in a larger heat rejection. A deeper borehole is costlier and has to be evaluated. Due to subsurface heat rejection the temperature increases. This negatively impacts the ability to reject heat to the subsurface and therefore decreases the efficiency of the heat rejection.

IV. PREFACE

This report is intended to give insight into the situation considering air-conditioning in Oman. During a 4.5-month research at the German University of Technology in Oman a model has been constructed that will help in determining feasibility of using absorption cooling. The ambient air temperature is too high for efficient heat rejection and therefore subsurface heat rejection is deemed necessary. For outsiders the relevance of air-conditioning is not that obvious, however for everyone that has spent some time in the Middle East, the relevance of air-conditioning is undeniable. Towards the end of the internship when more hours were spent working on the research over the weekend -when the air-conditioning was not switched on and indoor temperatures reached 30^{0}C- the necessity of these systems could not be more apparent.

Often in the weekends accompanied by Prof. Dr. Ekkehard Holzbecher, patiently taking the time to explain aspects of heat modelling and helping to find solutions to emerging modelling challenges. Thank you kindly for the educational experience and the opportunity to work in a country that is entirely different from anything I have encountered so far.

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VIII. ABBREVIATIONS & SYMBOLS

Abbreviation	Definition
BHE	Borehole Heat Exchanger
CFCs	Chlorofluorocarbons
COP	Coefficient of Performance
COP21	21st Conference of the Parties
DPS	Dhofar Power System
EER	Energy Efficiency Ratio
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HCFCs	Hydrofluorocarbons
HVAC	Heating, Ventilation and Air-Conditioning
INDC	Intended nationally determined contribution
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
MIS	Main Interconnected System
NPV	Net Present Value
OECD	Organization for Economic Cooperation and Development

PAEW	Public Authority for Electricity and Water
PBT	Payback Time
PDO	Petroleum Development Oman
RAEC	Rural Areas Electricity Company
TRC	The Research Council
UNFCC	United Nations Framework Convention on Climate
UTES	Underground Thermal Energy Storage

Symbols Latin	**Unit**	**Description**
t	sec	time
c_P	J/kgK	heat capacity at constant pressure
V	m^3	volume
T	K	temperature
A	m^2	surface
Nu	-	Nusselt number
l	m	length
Re	-	Reynolds number
g	K/m	Geothermal gradient
x, X	m	length position
r, R	m	radial position
m	kg	mass
k	W/(mK)	thermal conductivity

Subscripts	**Description**
eq	porous medium
s	solid
f	fluid
th	thermal

Symbols Greek	*Unit*	*Description*
ρ	kg/m^3	density
α	m^2/s	thermal diffusivity

1 INTRODUCTION

Together with the TU Berlin, The Research Council (TRC) of Oman and GFZ Helmholtz (Potsdam) a pilot project has been set up to develop a unique concept for a continuously operating absorption cooling system based on renewable energy resources. This Continuous Hybrid Cooling system will use geothermal heat sinks and storage (heat provides base load heat supply whereas solar heat supply fluctuates). Combining the solar heat source together with underground thermal storage systems to stabilize the supply system, could offer a formidable solution to reduce (non-renewable) energy consumption by air-conditioners. In this research the focus shall be on the subsurface segment of the system. Heat modelling is used to simulate the subsurface heat flows and can help with efficiency and feasibility determination.

2 BACKGROUND

The Sultanate of Oman (Oman) is located in Asia on the Arabian Peninsula, bordering the United Arab Emirates, the Kingdom of Saudi Arabia and the Republic of Yemen. Oman has a geographically spread population of approximately 3.6 million people. The country has a subtropical hot desert climate with very high temperatures (+40 °C) in summer and low annual rainfall. The economy relies heavily on the oil and gas sector, accounting for 51% of Gross Domestic Product (GDP) (Trading Economics, 2016). Natural gas use in the domestic sector has more than tripled from 2000 to 2012 (IRENA, 2014). In the electricity sector 97.5% of the countries power generation is derived from natural gas (IRENA, 2014).

There are three main electricity systems in Oman. The Main Interconnected System (MIS) is the largest (776,153 accounts) -containing three electricity companies and interconnecting seven power plants- and serves the majority of people in Oman. Then there is the isolated Dhofar Power System (DPS) (84,127 accounts) in the south of Oman. The remaining rural areas are supplied with electricity generated mainly by diesel generators, run by Rural Areas Electricity Company (RAEC) (30,904 accounts) (AER, 2015). The residential sector is by far the largest consumer of electricity, representing nearly 50% of the total system energy supply of the MIS.

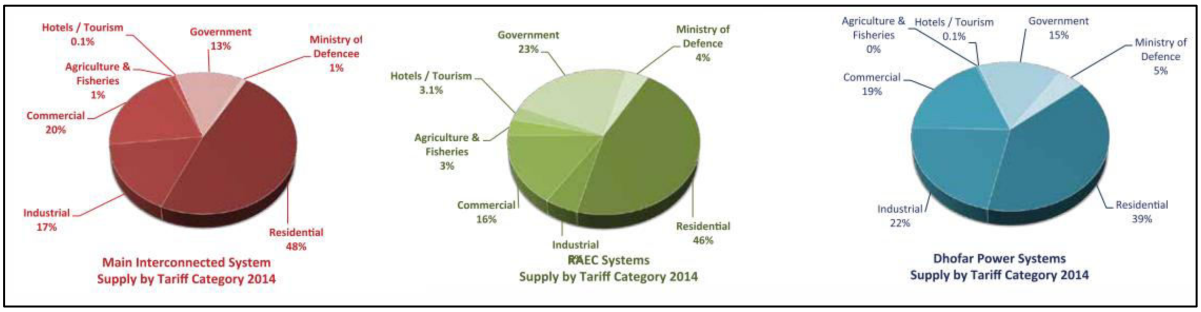

Figure 2-1: Electricity Supply by Tariff Category 2014 (AER, 2015)

The annual electricity demand curve is a good representation of the geo-climatic conditions in Oman, as it highly seasonal. Due to growing recognition of air-conditioners as necessary appliances and their intensified use, there is a sharp increase in residential electricity demand during summer. As of yet there seems to be no good alternative for electrical air-conditioners. The peak summer demand is more than twice the peak demand in winter as can be seen in Figure 2-1 (Qader, 2009).

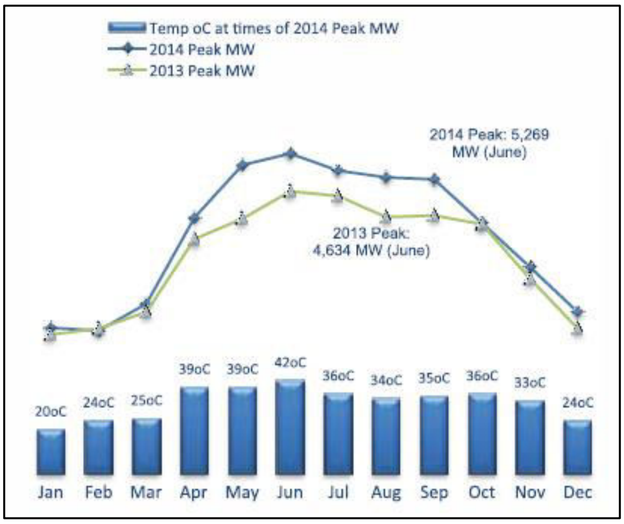

Figure 2-2: MIS Peak Demand 2013 & 2014 (AER, 2015)

The 2014 gross electricity production of 29.13 TWh increased by 11% compared to the 2013 production. The electricity (and water) sector saw a 7.8% increase in gas consumption in 2014 compared to 2013 (AER, 2015). This annual increase rate is expected to continue and peak demand is expected to rise (9% increase for MIS and 10% increase for DPS) due to: an increase in population, economic development and accelerated development of industry and tourism (AER, 2015; A. H. Al-Badi, Malik, & Gastli, 2009; Kazem, 2011).

3 SOCIETAL BACKGROUND & PROBLEM

3.1 Agreements

From the 19th of April 2005 Oman became a member party of the Kyoto Protocol. This implies that the Sultanate is committed to make improvements towards reducing its environmental impact and greenhouse gas (GHG) emissions.

In the Intended Nationally Determined Contribution (INDC), submitted before the 21st Conference of the Parties (COP21) in Paris, Oman has committed to reducing its GHG emissions by 2% to approximately 88.7 kilotons from 2020 to 2030. The INDC is the action plan that has been submitted to the United Nations Framework Convention on Climate Change (UNFCCC) and contains several measures to reduce emissions. The main measure for emission reduction is increasing the share of renewable energy in the total energy outlook (MuscatDaily, 2015).

3.2 Potential

According to a study done by COWI and Partners (COWI, 2008) Oman offers great potential for application of renewable energy resources. The solar energy density level is amongst the highest in the world and offers potential to supply sufficient electricity for Oman's domestic requirements. There is also significant potential to use wind energy for electricity production. This offers an opportunity for energy and economic diversification. Even though Oman has a large potential for renewable energy, it currently has no role in the country's energy supply. Doing research and development could aid the deployment of renewable energy sources in Oman and would create new business, shifting the Omani economy away from being Oil and Gas based. Other Gulf countries are exploiting such opportunities (IRENA, 2014).

3.3 Barriers

The development of renewable energy in Oman faces many political and administrative barriers. The highly subsidized supply of electricity ($1.17 billion[1] in 2015; (Reuters, 2016)) bridges the gap between the costs of producing and supplying electricity and the low electricity tariffs. In 2012 this corresponded to nearly 42% of the production and supply costs. Besides the financial subsidy the fuel for electricity production is sold far below the opportunity cost (international market price). This doesn't only result in significant costs and revenue losses for the government, it also opposes necessary fiscal incentive for consumers to install renewable technologies. Besides, it increases the requirement for gas, generating a shortage in future supply when compared to increasing demand (A. H. Al-Badi et al., 2009; IRENA, 2014).

3.4 Necessity & Strategy

Oman's oil and gas resources aren't sufficient to support the current consumption trend and therefore shortages of electricity are expected to occur. According to Kazem (Kazem, 2011) if Oman continues building electricity stations that consume gas it will have to start importing gas instead of exporting it. A general awareness that the economy has to diversify, from oil and gas-based to a more stable economic situation with enhanced energy, seems to be emerging (IRENA, 2014).

The Council of Ministers has requested the Ministry of Finance and the Public Authority for Electricity and Water (PAEEW) to create an energy strategy. The future strategy to enable the role out of renewable energy resources in Oman entails five main aspects:

1. Develop policy and regulatory framework to promote the application of renewable energy
2. Create an implementation model for targets and markets
3. Create an institutional and legal framework to secure efficient implementation
4. Do resource mapping, research and development of renewable energy sources
5. Build local capacity for a sustainable business model

(A. H. Al-Badi, Malik, & Gastli, 2011; IRENA, 2014)

4 KNOWLEDGE GAP

Contrary to the large potential and the abundance of renewable energy resources in the region, the availability of governmental subsidies for oil and electricity generation and lack of such subsidy for renewable energy, has restrained investment, development and competitiveness of/in sustainable resources. Also the lack of interaction with policy makers, manufacturers and potential users and the absence of dissemination and application of scientific knowledge have been notable constraints (Patlitzianas, Doukas, & Psarras, 2006).

The amount of research on Oman's potential for usage of renewable energy was very limited. The Omani government hadn't conducted any significant studies to ascertain the environmental and economic impacts of deployment of renewable energy systems in Oman. Now sufficient financial and intellectual resources are available, political decisions are being made to come to pace with the rest of the world (A. H. A l-Badi et al., 2011; COWI, 2008). In 2015 an estimated 27.7% of the world's power generating capacity was provided by renewables, this is enough to supply an estimated 22.8% of global electricity (REN21, 2015).

[1] This is an understatement as the government is also selling gas at a subsidized rate for electricity generation.

It is clear from the residential electricity consumption (approximately 50% of national consumption) and the estimated large contribution of electricity consumption by residential air-conditioners, that a large share of national GHG-emission can be attributed to air-conditioners. There is no report that specifically states these consumption and emission data and therefore research has to be done into this matter.

4.1 Geothermal Energy

In previous studies assessments have been made for feasibility of electricity generation through geothermal energy. Locations of boreholes and temperature maps of 500 m and 1,500 m depth of the Petroleum Development Oman (PDO) have been evaluated. The highest temperature encountered was 174 ^{o}C. This isn't sufficient for direct use in steam power plants (A. H. Al-Badi et al., 2009; COWI, 2008).

The characteristics of the subsurface that have been decisive in this research are however that the temperature is relatively constant and lower than the ambient air temperature. The subsurface heat rejection is necessary because the ambient air temperature is too high to run the system effectively. The initiated set up has so far been focussed on the installation above the ground. Research will have to be conducted into the feasibility of using a well with water flowing through (borehole heat exchanger) as a heat sink and into geothermal storage possibilities. Heat rejection of the system is an important parameter that determines the Coefficient of Performance (COP).

The potential of low grade thermal energy for usage in the Continuous Hybrid Cooling system hasn't been evaluated yet. Subsurface temperature measurements will have to be done and used as input to establish an understanding of the geothermal conditions. Also the thermal conductivity is an important measure to determine the potential heat rejection and possibility of geothermal storage. These characteristics will be used as input in COMSOL Multiphysics™ -a physics based modelling and simulation program- to estimate the impact this will have on the subsurface conditions and in response on the efficiency of the cooling system.

The successful implementation of the Hybrid Cooling system is dependent on feasibility and marketability of the installation. Therefore, research has to be done into the operational characteristics of the system, the theoretical emission reduction that can be realized, the potential costs savings etc. The solar collector and absorption cooling part of the research was mainly conducted by the counter part of the team residing at the TU Berlin. The outputs of their research could be used as inputs for this research in a later phase.

5 RESEARCH QUESTIONS & PROBLEM DEFINITION

Research Question	**Is absorption cooling possible for the climatic conditions in Oman?**
Sub Questions	What is the maximum obtainable heat rejection to the subsurface? What impact does heat rejection to the subsurface have on the subsurface temperature? How does this impact the efficiency of the system?
	The focus when answering the research questions was on the subsurface area of the system. The answers to these questions should provide a clear understanding of the subject area.

Scientific background	Energy science / Environmental science
Thematic field	Sustainability / Energy efficiency / Climate change
Assumption	Large scale implementation of the Hybrid Cooling System could lead to a significant reduction in residential electricity consumption. In Oman unsustainable electricity generation leads to high CO_2 emissions. CO_2 is a greenhouse gas and is one of the main drivers for anthropogenic climate change (global warming). Reducing human induced CO_2 emissions is environmentally and socially desirable. 1,500 kW heat rejection and 200 m^3/h of water (refrigerant) flowing through the borehole are assumed parameters for efficiently running the absorption cooling system.
Knowledge gap	The emissions that take place during electricity generation that can be allocated to air-conditioning; the potential reduction in electricity consumption and the associated cost reduction; performance of the system under non-optimal temperature conditions; the impact of heat rejection to the subsurface and the impact this will have on the system (e.g. efficiency).
Research relevance	Research to close the knowledge gap is valuable as there is currently little research done into the GHG emission of residential air-conditioning in Oman. The estimated contribution of GHG emissions from air-conditioning is large and therefore an improvement in this segment has the potential to reduce emissions and positively impact the environment. Electricity generation in Oman is mainly done by gas combustion. If due to more sustainable air-conditioning a reduction in electricity consumption can be realized, a share of the national gas production becomes available (e.g. for export). It is expected that if the current level of gas consumption continues, Oman will have to start importing gas shortly. The Research Council of Oman, TU Berlin and GFZ Helmholtz Centre have initiated a pilot project to establish a Continuous Hybrid Cooling for a new building in Oman. It is estimated that 1,500 kW heat rejection is necessary to run the absorption cooling system efficiently. The targeted water volume flowing through the borehole is 200 m^3/h. The target of this research was to evaluate whether this is a feasible scenario given the circumstances of Oman.
Function	The function of this research was to determine the feasibility of the Hybrid Cooling system in Oman.

6 METHODOLOGIES

The research had a scientific modelling approach. The goal of this model was to simplify an occurring phenomenon and make it easier to understand. This would enable further calculations with the representation of reality and finally gave the ability to make predictions about the feasibility of the Hybrid Continuous Cooling system.

The following basic principles were applied:

Method	To establish a good understanding of the subsurface an interpretation of the subsurface was made by modelling. This was initially done with data derived from literature and by comparing the Muscat region with areas that have similar characteristics. The data was used to create a model in COMSOL Multiphysics. The parameters were subjected to a parametric sweep to assess the sensitivity on the results of parameter variation.
Data	The sources of data that formed a basis for this research were: academic articles from scientific databases (e.g. Researchgate); data that was made available by TRC, TU Berlin & GFZ Helmholtz; data from research institutes (e.g. IEA); data that was derived from own borehole measurements on site.

6.1 Preparation

The preparation phase consisted of getting acquainted with the subject. It was useful to gain a broad understanding of absorption cooling, its appliances, the chemistry driving the system, solar energy functioning as heat source, Oman's geo climatic conditions etc.

This information was gained by doing literature review, reading existing material from the research group, talking to experts on the subject matter, reading subject related articles and other available (scientific) sources.

6.2 Data Gathering and Temperature Measurements

In the initial phase of the research, data was taken from sources describing comparable environments or when available from sources describing the local environment. There were two boreholes on the German University of Technology (GUtech) in Oman's campus. In May a borehole temperature measurement apparatus was supposed to be available (from the research group in Germany) that would enable accurate down-hole analysis. This was postponed until September, therefore an estimation of the subsurface temperatures was made based on previous knowledge and water level measurements were done with the available depth gauge.

The data was entered into the model to gain a good understanding of subsurface conditions. TU Berlin has provided some data that was used as input for the subsurface modelling exercise.

6.3 Model constructing

The COMSOL Multiphysics program offered a great variety of models. A choice had to be made on which type of model the best representation of the reality could be displayed. Different aspects of physics, rheology and thermodynamics were taken into account and a decision was made to start from a prior constructed model based on existing data.

A balance between a good representation of reality and not creating a too complex model had to be made. The model was chosen for the ability to adjust parameters and give a quick representation of reality, rather than a too complex model that is hard to adjust and sensible to errors.

The model could be validated by estimating what the parameters should be based on prior knowledge of the process or existing data and by comparing the outcomes to the data supplied by TRC.

6.4 Testing & Comparing

Multiple methods exist to test the adequacy of the outcomes. Sensitivity analyses by means of parametric sweep was used to assess the impact of variations in inputs and potential differences in outcomes and to investigate the uncertainty of the variables.

Several model runs, the sensitivity and uncertainty analysis and the supplied data to assess the adequacy and accuracy of the output of the model were compared.

7 SCIENTIFIC BACKGROUND

Air-conditioning is an essential part of comfortable life in the Middle Eastern region. The standard cooling machines consume a lot of electrical energy. Since the majority of this energy is generated by burning fossil fuels, they are responsible for a large share of the GHG emissions in the Arabian Peninsula. According to Najib Saab, secretary general of the Arab Fund for Environmental Development, Gulf Cooperation Council (GCC) countries could save up to 40% on their energy bills by developing energy efficient products (Economist, 2010).

The pilot project to develop a unique concept for a continuously operating Hybrid Cooling system based on renewable energy resources (Fig. 3) will use solar heat and geothermal heat sinks and storage. The geothermal heat will provide base load heat supply whereas solar heat supply fluctuates. Combining the solar heat source together with underground thermal storage systems to stabilize the supply system, could offer a formidable solution to reduce (non-renewable) energy consumption by air-conditioners.

7.1 Absorption Cooling

The absorption cooling system uses thermal energy to produce cooling. Solar and thermal energy can be employed as low grade heat sources. No Chlorofluorocarbons (CFCs) or Hydrochlorofluorocarbons (HCFCs) (conventional refrigerants) are used in the process, making it an environmentally friendlier system (Assilzadeh et al., 2005).

The absorption air-conditioning uses vapour compression in different pressurization stages to create a cooling effect. An absorbent (e.g. LiBr) in the low-pressure side absorbs the evaporating refrigerant (H_2O). The strong affinity between the chemical fluids makes the cycle work (Assilzadeh et al., 2005; Johnsons Control Inc., n.d.).

The subsurface heat rejection is necessary because the ambient air temperature in Oman is too high to run the system effectively. The subsurface temperature is lower than the ambient air temperature. The initiated set up has thus far been focussed on the installation above the ground.

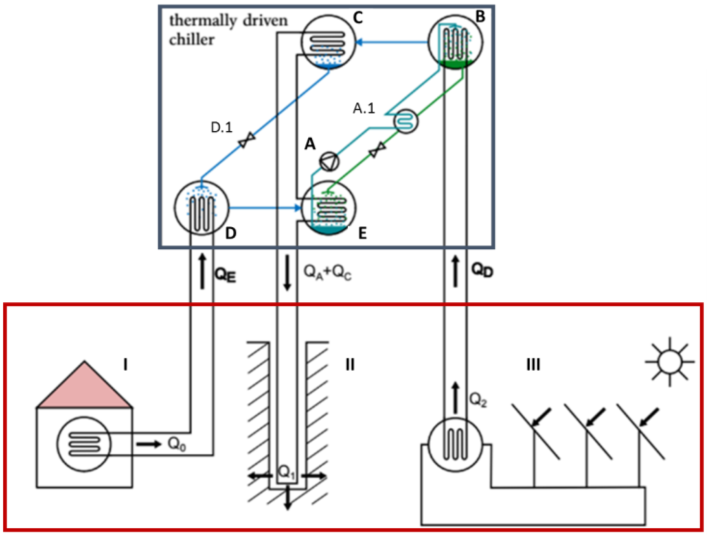

Figure 7-1: Thermally Driven Chiller composition (TU Berlin, 2016)

Source ("YIA Absorption Chiller," n.d.):

A. Solution Pump

In the bottom of the absorber shell (E) a diluted lithium bromide solution is collected. The solution is pumped with the hermetic solution pump to the upper shell, through a tube heat exchanger (A.1) for preheating.

B. Generator

The dilute solution moves from the heat exchanger to the upper shell where it surrounds a bundle of tubes, carrying hot water or steam. Heat is transferred from the hot water or steam to the solution. This causes the solution to boil and the refrigerant (water) vapour moves to the condenser. A concentrated solution of lithium bromide moves back down to the heat exchanger (A.1), to heat the weak solution that is pumped up to the generator.

C. Condenser

The water vapour moves through mist eliminators to condenser tube bundles. These condense the refrigerant vapour, removing the heat with the cooling water running through the tubes. The refrigerant liquid is collected in a through at the bottom of the condenser.

D. Evaporator

The water is lead (D.1) from the condenser to the evaporator and sprayed over the evaporator tube bundle. The extreme vacuum in the lower shell (6mm HG (0.8kPa) absolute pressure) causes the water to boil at 3.9 ^{o}C, causing the refrigerant effect. The strong affinity lithium bromide has for water causes the hygroscopic effect creating the vacuum in the absorber.

E. Absorber

After the evaporator the water vapour is moved to the absorber. The strong lithium bromide solution that has come from the generator (B) and heat exchanger (A.1) is sprayed over the absorber tube bundle. The strong solution creates the vacuum by 'pulling' the water vapour into the lithium bromide solution. The absorption of the refrigerant vapour into the solution generates heat. This is removed by the cooling water. The dilute solution of refrigerant and lithium bromide is collected at the bottom of the lower shell and flows to the solution pump (A).

I. Residence

The temperature of the residence is variable but must be kept at a comfortable range. The average ambient temperature varies between 40 ^{o}C in June and 25 ^{o}C in January (Huenges, Schütz, & Al-riyami, 2016). The heat load that has to be extracted from the residence will therefore vary throughout the season and was modelled accordingly.

II. Heat Sink

The heat rejection will take place in a subsurface well because the ambient air temperature is too high to reject the heat to efficiently. The reject heat temperature was modelled at 40 ^{o}C. It is expected that 1.5 MW of thermal energy needs to be rejected at a flow rate of 200 m^3/h. The thermal energy transferred is proportional to the mass flow rate (Huenges et al., 2016).

III. Solar Collectors

The solar collectors supply the driving heat. This must be between 70 ^{o}C and 110 ^{o}C for a COP of 0.8 to 0.5 (Huenges et al., 2016).

7.2 Technology

In order to create a comfortable thermal environment, the typical heat pump for air-conditioning uses electricity to remove heat from the cold source location. In air-conditioning the ground source heat pump (GSHP) uses the subsurface to reject heat to. Due to the relatively constant geothermal environment the GSHP in theory has a higher efficiency than conventional air to air or air to water heat pumps (Qian & Wang, 2013).

7.2.1 History and Current Applications

The first recorded concept of utilizing the thermal potential of the ground as a heat source for a heat pump was recorded in a Swiss patent published in 1912 by Heinrich Zoelly (Ball & Hodget, 1983). Due to technological difficulties and the low efficiency of heat pumps it was not until 1945 that the first prototype GSHP was used for space heating. Commercial application of the GSHP was developed after the oil crisis of 1973. This boosted the interest in the different GSHP applications in multiple countries (Qian & Wang, 2013). The GSHP systems offer significant energy consumption reductions from the power grid and therefore form attractive solutions for residential and commercial cooling (and heating). According to the IEA (IEA, 2010) there was around 50.6 GW_{th} capacity installed for direct use in 2009. With around 50% or 220 PJ the GHSP's formed the largest contributor in direct use. At the end of 2014 the estimated installed geothermal power for direct utilization is 70.3 GW_{th}. This is nearly 45% increase compared to the 2010 data (Lund & Boyd, 2015). Heat pumps in the cooling mode are not included, as they only return heat to the subsurface, but the large increase in the heat pumps' installed capacity can be seen as indication for the increase of usage for cooling purposes as well.

7.2.2 Borehole Heat Exchanger

The borehole heat exchanger (BHE) is a major part of the GSHP. It is a borehole that carries a fluid (usually water) into the subsurface and allows for the exchange of heat. After exchange of heat the fluid is returned to the surface, in a closed or open system. There are multiple configurations for the BHE, with different designs (e.g. the co-axial borehole, the U-pipe and co-axial with peripheral flow channels) and borehole depths. The length that is required for a certain output of the BHE depends on subsurface characteristics (e.g. temperature, moisture content, groundwater flow etc.) and design characteristics (e.g. shape, borehole filling, heat transfer coefficients etc.) (Sanner et al., 2003).

7.2.3 Efficiency

Besides the characteristics mentioned above, the efficiency of the BHE is impacted by pipe positioning, potential low conductivity of grouting or subsurface material, thickness of the pipes and thermal contact between pipe channels (Acuña & Palm, 2011). High efficiency heat exchangers are characterized by a low thermal resistivity, which is important for the dimensions of the borehole and therefore also the costs of the facility. When the BHE is coupled with a solar heating system for recharging the subsurface ambient temperature (or heat rejection) this becomes of even greater importance. Thermal efficiency is of crucial importance to ensure high efficiency of the GSHP system (Luo et al., 2013; Oberdorfer, 2011).

7.2.4 Decrease of Efficiency

When the GSHP system is not properly designed and in warm regions the heating load is not balanced, heat accumulation can occur. The heating load in the subsurface can be larger than the subsurface can digest the heat, leading to an increase of the subsurface temperature. This decreases the difference between the subsurface temperature and the temperature in the BHE, which in turn reduces the efficiency of the GSHP system. The increase in subsurface temperature leads to a decrease in moisture content of the soil, which leads to a notable decrease in conductivity. These combined effects will reduce the cooling energy of the GSHP and may lead to the system not satisfying the requirements on a larger timescale (Qian & Wang, 2013; Yu, Ma, & Li, 2008). According to Qian and Wang (2013) is therefore not suitable for regions where the cooling load is much larger than the heating load.

There is a significant difference between designs of a closed-loop GSHP and ASHP. Unless there is a large groundwater flow, the primary heat transfer mechanism is conduction and convection respectively. As mentioned above, the temperature of the ground surrounding the BHE is likely to rise over the course of a year when there is mainly heat rejection taking place. Keeping the change within acceptable limits over the lifetime of the system must to be taken into account when designing a GSHP system. The method of designing has to be based on the cooling load throughout the year and not only for the peak load. This implies that more research is necessary concerning the building loads than for a conventional ASHP system (Spitler, Rees, & Yavuzturk, 2005).

7.2.5 Heat rejection

The extreme climate in Oman creates a challenge for the discharge of waste heat. The subsurface heat rejection is deemed necessary to run the absorption cooling process efficiently because the ambient air temperatures are too high for effective heat rejection. The subsurface environment has a much more stable climate and if there is a dynamic aquifer the heat could be removed without impacting the subsurface too much.

7.2.6 Heat storage

The concept of underground thermal energy storage (UTES) could be useful for the storage of solar and waste heat and potentially be used for cooling purposes (Sanner et al., 2003). The low thermal conductivity of the subsurface allows for energy to be stored when there is a surplus and retrieved when required. The natural substratum (the rock and groundwater) serve as the storage medium. In renewable systems as (solar) absorption coolers energy storage at low temperatures can significantly add to the capacity factor. At night there is no solar energy driving the system and the stored thermal energy can be extracted from the subsurface to continually drive the absorption cooling process. When the aquifer is charged (i.e. heat flows into the aquifer), warm water forms around the borehole. For the heat storage to be effective, this warm water must remain in situ and not be influenced by groundwater flow too much. When there is an energy requirement the aquifer can be discharged and the warm water will be pumped out of the subsurface again.

There are different UTES possibilities. One can use a closed loop system; the borehole thermal energy storage or an open system; the aquifer thermal energy system. Which of these systems will be used depends on multiple factors. Geological research and legislative investigation must be done before the must suitable option can be chosen.

7.3 Economic Feasibility

For a sustainable energy system to be adopted on a large scale it has to be economically feasible. In general the economic affordability is measured by the costs of a technology compared to the price that a buyer would be willing to pay for it. This means that for market penetration and a widespread adoption, the price level of a certain product has to be competitive with the conventional product. As for many sustainable energy systems, the ground coupled absorption cooler -or a comparable system- is not price competitive yet. Increasing environmental awareness and a change in governmental contributions and subsidies could change this. The advantage of a ground coupled absorption cooler or a GSHP depends strongly on the local conditions. The relevant working parameters may differ significantly per region. It is of great interest for Oman to look abroad and see whether there are examples of successful implementation of comparable systems.

In a study done by Said et al. (Said, Habib, Mokheimer, & El-Sharqawi, 2010) it was concluded that in the Kingdom of Saudi Arabia the temperature difference between the ambient air and the subsurface favours the performance of the GSHP over that of air-cooled exchangers. There is a noticeable increase in the coefficient of performance and in the energy efficiency ratio (EER) (table 2) when using a GSHP instead of an air-cooled condenser. In Saudi Arabia the implementation of GSHP in residential buildings has the potential to reduce energy consumption by air-conditioning systems by 14-20%. However, with the low electricity tariffs, of approximately 7US¢/kWh, in December 2009, and drilling costs of approximately US$ 1800-2900 for a 30m deep well, the use of a GSHP would not be economically beneficial. If the price of electricity were to change, or if for example carbon pricing would be implemented the economic situation could change in the favour of the GSHP.

Table 7-1: Energy Savings.(Said et al., 2010).

Heat sink	Ambient temperature (^{0}C)	EER[a]	Power consumption (kW)	Energy consumption (kWh/year)	Energy savings (kWh/year)	Number of central ACs	Total energy savings from all central ACs (kWh/year)
Air	46.1	6.264	15.33	58,238		390,000	
Ground[b]	32.2	7.809	12.29	46,715	11,523		4494×10^6
Ground[c]	36.4	7.313	13.13	49,886	8,352		3257×10^6

[a] Energy efficiency ratio was calculated using the DOE/ORNL Heat Pump Design Model Mark IV software.
[b] Measured mean borehole temperature during short term tests.
[c] Averaged over 30 years.

Table 7-2: Cost analysis and reduction in CO_2 emissions if GSHPs would replace 390,000 central ACs in the KSA. (Said et al., 2010).

	Assumed electricity tariffs (US_c/kWh)				
	1	3	4	5	7
Net additional costs; fixed performance (10^6 US$/year)[a]	806.7	746.9	686.9	626.9	567.2
Net additional costs; averaged degraded performance over 30 years (10^6 US$/year)[a]	823.2	779.7	736.3	693.1	649.6
Reduction in CO_2 emissions	2.73 x 10^6 tons/year (based on fixed performance) 1.98 x 10^6 tons/year (based on averaged degraded performance of 30 years)				

[a] Based on December 2009 Saudi Arabian Riyal and US dollar rate of exchange.

According to Kharseh et al. (2015) the application of GSHP in heating and air-conditioning in agricultural applications in Syria results in 31% reduction of energy consumption.

In Qatar Kharseh et al. (2015) have done research into the potential financial benefits of GSHP systems. Net present value (NPV), internal rate of return (IRR) and the payback time (PBT) were taken into account for the economic analysis. For the analysis the escalation rate of the electricity price, the initial investment cost of the system and the annual saving of income have to be known.

Kharseh et al. found that the annual cooling load in Qatar is high with around 251 kWh/m2. For each MWh of cooling load 6.9 m borehole depth is required and 21.4 m per kW of cooling capacity. Applying GSHP systems leads to reduction in energy consumption and therefore the GHG-emissions derived from air-conditioning decrease by 19%. The IRR is 14.3% for residential buildings and the PBT of the system is 9 years.

The authors state that the research has been done in Qatar, but can be extended to all Arabian Gulf countries with comparable cooling requirement conditions.

Esen et al. (2007) did an economic comparison between air source heat pumps and (shallow) GSHPs in Turkey. They found a PBT of around four years for a GSHP compared to an ASHP, owing to the cheaper installation costs of the ASHP but the lower running costs of the GSHP.

In Europe most countries don't have widespread hydrothermal resources that could be used for direct application. There isn't the same necessity for air-conditioning as in the GCC, therefore abundant shallow geothermal resources are a widely adopted option in GSHP systems, for heating mainly. There is a rapid increase in the number of commercially operating ventures in the field of GSHP's (Sanner et al., 2003).

According to Tagliabue et al. (2012) the cost of applying a sustainable solution for air-conditioning is no higher than the simplest system used in a wide variety of Italian buildings; gas powered thermal systems coupled with low performance plant for air-conditioning in the summer. The cost effectiveness of a technological improvement is decisive in the market penetration of the new solution. According to the EU Energy Performance for Buildings Directive (EPBD) the cost to achieve economic feasibility has to be reviewed every five years. The costs of an technological improvement of today have to be reviewed with the expected future costs derived by the market trend evolution (Tagliabue et al., 2012). However, the capacity factor of air-conditioning in Europe is very low. Capital investment, whether relatively marginal and decreasing over time, isn't favourable in a low capacity factor scenario.

7.4 Impact on environment

Besides the potential economic upside of implementing energy efficient cooling systems the main goal is reducing the environmental impact. Heating, ventilation and air-conditioning (HVAC) systems are known to play a crucial role in energy consumption by buildings and together attribute to a large share of global energy consumption. It is expected that significant energy reductions can be realized by applying renewable energy technologies. To be able to make a statement about the impact that a proposed system might have on the environment, potential benefits and disadvantages must be compared. There are examples of hydraulic dams for electricity generation that have emitted far more GHGs than would have been done for the same electricity generation by fossil fuel combustion, defeating part of the purpose. It is therefore of great importance to consider the entire system.

Aquifer temperatures in urban areas are 1-5^{o}C higher than in rural areas, primarily as a consequence of urbanization (Gunawardhana, Kazama, & Al-Rawas, 2015). Increasing the subsurface temperature above the natural range is considered pollution. The subsurface temperature is largely impacted by the BHE. This affects temperature changes in groundwater ecosystems like estuaries, ponds and wetlands, with potentially critical effects (Gunawardhana et al., 2015). When the number of geothermal energy systems within a certain area increases, the efficiency of the systems decreases, offsetting the benefits and the impact on the environment deteriorates. These effects increase when the BHEs are placed in a suboptimal distance from each other.

7.5 Legislation and Drinking Water

In a research done by Haehnlein et al. (2010) 35 of the 46 countries didn't have any regulations or guidelines for the use of geothermal energy. There are countries where the legal regulations or guidelines were imposed dependent of the minimum distance to the next geothermal system, property line or building and on the temperature threshold for the effect on the environment (Gunawardhana et al., 2015). The temperature change of groundwater at 50 m distance from a BHE (or geothermal system) can't be more than 2^{0}C in Stuttgart and in Denmark at least 300 m distance is required between a geothermal system and a drinking water well. The absence of widespread and clear international regulations concerning ground water and geothermal energy systems is because to a large extent the impact of such systems remains unclear. Groundwater is considered a very important and potentially vulnerable facet of the environment with great value to society. Due to a lack of scientific analysis concerning the subsurface geothermal energy threshold values can vary greatly between countries and sometimes appear rather arbitrary (Gunawardhana et al., 2015).

Oman has a significant overconsumption of the groundwater resources. Since 1988 governmental laws and regulations are in place that protect the water resource from depletion and pollution. In a Royal Decree the regulations are stated that should protect the groundwater. The main regulation that could impact the groundwater utilization for geothermal energy is the Royal Decree 82/88: 'The water of the Sultanate of Oman is a national resource to be used according to the restrictions made by the Government for organizing its optimum utilization in the interest of the state of comprehensive development plans.'

In a closed system GSHP the impact of heat rejection is expected to be limited, but when using an open system and drilling into aquifers the impact can be hard to predict. The increased and ungoverned abstraction of groundwater over the past decades has led to deterioration of the quality of the groundwater in some regions. Increased salt water intrusion and salinization of soil due to a reversal of the groundwater flow from seawards to landwards is one of the negative consequences of overexploitation.

8 MODEL

8.1 Subsurface heat

Heat is the form of energy that can be transported between systems as a result of temperature difference (Cengel & Ghajar, 2015). The heat transfer always takes place from a higher temperature region towards a lower temperature. When the two regions are in equilibrium the heat transfer stops. When there are a heat source and an open system involved an equilibrium doesn't have to be reached. There are five modes for heat transfer to take place in the soil: conduction, convection, radiation, advection and phase change or evaporation.

8.2 Conduction

Conduction is the transfer of energy in solids, liquids or gases, from the more energetic particles to the less energetic particles. Conduction is the dominant mode of heat transfer at (larger) depths in the subsurface. In the shallow subsurface other heat transfer processes play an important role (Rutten et al., 2010). Conduction is the result of interactions between the adjacent particles. In solids conduction takes places due to vibrations of the molecules in a lattice and the transport of energy by free electrons. The rate at which heat conduction takes place through a medium is dependent of its thickness, the material, the geometry and the temperature difference across the medium (Cengel & Ghajar, 2015). The heat flux is always proportional to the temperature gradient, the constant of proportionality (k) is the thermal conductivity.

Fourier's law of heat conduction

$$\dot{Q}_{cond} = -kA\frac{\Delta T}{\Delta x} \tag{8.1}$$

Where A is the cross-sectional surface area, ΔT is the temperature difference between the ends and Δx is the distance between the ends.

8.2.1 Thermal Conductivity & Diffusivity

Each material has its specific heat c_p (e.g. $c_p = 4.18\ kJ/kg \cdot K$ for H_2O), which is an expression of a material's ability to store thermal energy. The thermal conductivity k expresses the ability of a certain material's ability to conduct thermal energy (e.g. $k = 0.3\ W/m \cdot K$ for very dry soil).

The thermal diffusivity is a method to express how fast heat diffuses through a certain material $\alpha = \frac{k}{pc_p}$. It is the ratio between the heat that is conducted through the material to the heat that is stored in a material.

8.3 Convection

Heat convection is energy transfer -the combined effects of conduction and fluid motion- between a liquid or gas in motion and the adjacent solid surface and is driven by density gradients. The amount of convective heat transfer depends on the speed of the fluid motion. The rate of convective heat transfer is proportional to the temperature difference.

Newton's law of cooling

$$\dot{Q}_{conv} = hA_s\,(T_s - T_\infty) \qquad [W] \tag{8.2}$$

where h is the convection heat transfer coefficient in $W/m^2 \cdot K$.

$$h = \frac{Nu \ \cdot k_W}{r_i} \qquad [\text{W/m}^2\cdot\text{K}] \quad (8.3)$$

Where Nu is the Nusselt number that depends on the flow regime in the pipes, the effective conductivity depends on the mean flow and constant parameters (Oberdorfer, 2011). In the linesource approach there is no flow regime in the pipes, therefore this does not have to be taken into account. An avareged constant flow velocity is considered through the pipes.

8.4 Radiation

Radiation of heat takes place in the form of photons (or electromagnetic waves) emission by matter due to changes in electronic configurations of atoms and molecules. Radiation becomes negligible and is not considered in subsurface heat transport processes because thermal radiation only takes place in (semi-) transparent materials and at the surface (or in the top few centimetres (Rutten et al., 2010)). This is because the radiation in opaque materials is usually absorbed within a few microns from the surface of the material (Cengel & Ghajar, 2015; Oberdorfer, 2014).

8.5 Advection

Advection refers to the scalar transport of a solute or heat that takes place due the bulk fluid motion (e.g. groundwater). Advection is considered together with convection in this research and will be referred to as convection (Comsol, n.d.).

8.6 Phase Change

Commonly referred to as latent heat or evaporation, phase change plays a role on the soil surface or the shallow subsurface. The phase change that takes place at the surface alone does not form an explanation for the heat source or sink at the surface. When vapour diffusion is considered as the limiting process, maximum values for the phase change are an order of magnitude smaller than the observed source –sink term (Rutten et al., 2010). Phase change forms a comparatively insignificant mode of heat transfer when considering the large depth at which the BHE operates and is therefore considered negligible.

8.7 Heat Transport

The subsurface heat transport in porous and fractured media is governed by permeability, fluid velocity or thickness of the porous medium and by the heat source or sink (Huenges, 2010). These parameters control the advective and conductive fluxes. The thermal conductivity and volumetric heat capacity are equivalent values for the current ratio of porous solid and fluid (Oberdorfer, 2014). The heat transport is determined by the partial differential heat transport equation.

$$\left(\rho c_p\right)_{eq} \frac{\partial T}{\partial t} + \left(\rho c_p\right)_f \boldsymbol{u} \cdot \nabla T - \nabla\left(k_{eq} \nabla T\right) = Q_T \qquad [\text{J/m}^3\cdot\text{K}] \qquad (8.4)$$

With following porous media properties:

$$\begin{aligned} \left(\rho c_p\right)_{eq} &= n\left(\rho c_p\right)_s - (1-n) \cdot \left(\rho c_p\right)_f \\ \mathrm{k}_{eq} &= n\mathrm{k}_s + (1-n)\mathrm{k}_f \end{aligned} \qquad (8.5)$$

(Huenges, 2010)

Where ρ is the density (kg/m^3), c_p heat capacity (J/kg·K), t is the time in seconds, $\boldsymbol{u}$ fluid phase velocity (m/s), k thermal conductivity (W/m · K), n is the porosity and Q_T the heat source (J/m^3 · K).

Heat transport in the pipes

$$A\left(\rho c_p\right)_f \frac{\partial T}{\partial t} + A\left(\rho c_p\right)_f \boldsymbol{u} \cdot \nabla T = \nabla \cdot A k_{eq} \nabla T + Q_T \qquad [\mathrm{J/m^3 \cdot K}] \quad (8.6)$$

8.7.1 From Down- to Upflow

At the turning point from the downflow to the upflow in COMSOL, the 1D linesources are connected with a linear extrusion. The temperature at the bottom of the downflow is a boundary condition for the temperature of the upflow. Because both pipes are considered linesources with an averaged temperature, there is no conversion calculation necessary and the temperature at the bottom of the downflow can be taken directly as input for the upflow pipe.

8.1.1 Domain

The choice for certain dimensions of the geometry has been done so that the heat transport processes are not limited or affected by boundary effects and so that the model is limited to a manageable region of interest. In the 2D model, COMSOL models a cross-section through an hypothetical 3D cylinder with the borehole wall on the inner boundary and an outer boundary at distance *R*. In the 3D model the outer boundaries were also chosen such that the horizontal heat transport processes were not disturbed and in a later stadium the groundwater flow could be evaluated at a sufficient distance.

8.1.2 Mesh

In the different models a specific mesh is chosen. In 1D the mesh is represented by calculation points, in 2D connected triangles and in 3D the mesh consists of an arrangement of free tetrahedrals. In 3D the tetrahedrals are generated in such a way the area of increased interest - around the BHE- has a higher density of tetrahedrals. At each grid point of the tetrahedrals the conditions are calculated by COMSOL. A higher density of tetrahedrals creates a more detailed view on the values in that part of the geometry. The higher resolution requires COMSOL to make more calculations, which increases the computation time and required memory and is not necessary for each model run. The number of degrees of freedom indicate the number of parameter

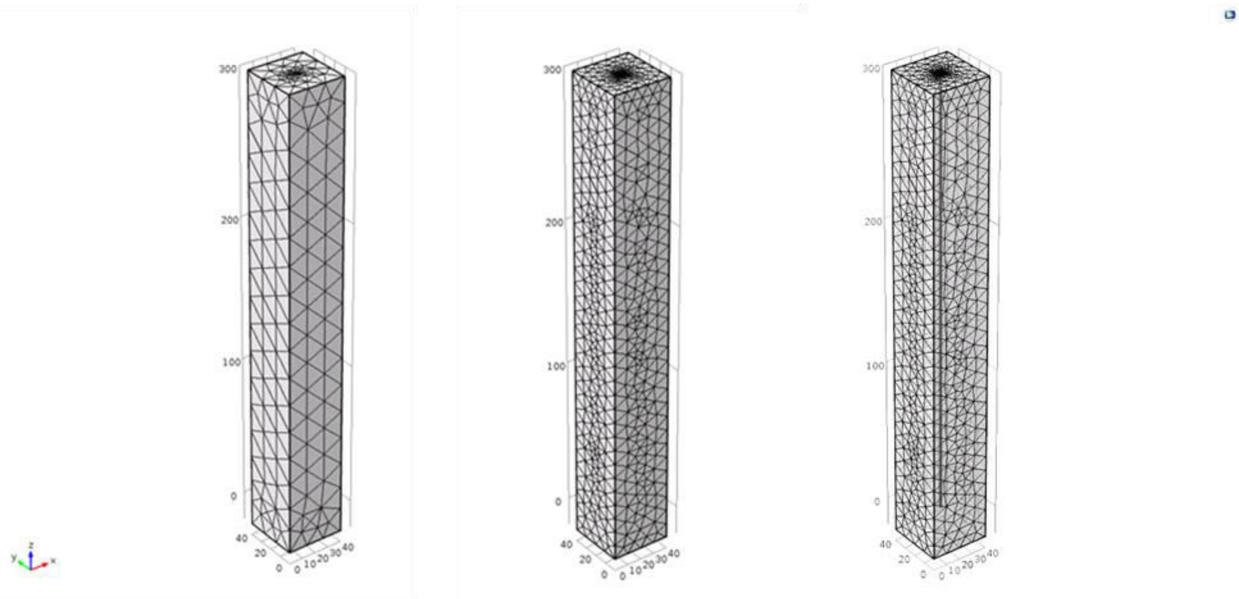

Figure 8-1: From left to right: Normal element size, complete mesh consists of 6,909 domain elements, 1,002 boundary elements, and 316 edge elements; Extra fine element, complete mesh consists of 321,155 domain elements, 12,068 boundary elements, and 2,680 edge elements; and Extra fine element size with transparent domains. All in 3D.

dependencies and the detail.

The choice between the different levels of detail is based on a balance between the necessity for accuracy and a reasonable computational time for each model run.

8.1.3 Parameters

In the first (2D) part of the model the subsurface is considered to be a solid. The parameters that are used for the subsurface are considered constant. The impact of these thermal and pressure dependent parameters is limited due to relatively small temperature and pressure (depth) variations. In later modelling attempts (3D model) the fluid fraction of the subsurface is taken into consideration. Here, the thermal and pressure dependencies are known and accordingly considered by COMSOL.

Table 8-1: (Fixed) Parameters subsurface models

Name	Value	Description
r_{in}	0.02 m	Inner radius BHE
d	0.0037 m	Thickness PE100
r_{out}	0.0575 m	Outer radius BHE
λ	4 W/(m·K)[1]	Thermal conductivity PE100
$\overline{\nabla}$	300 m	Depth
R	20 m	Outer radius model
T_{diff}	3 K	Heat pump difference
Q_{flow}	200 m^3/h	Flow rate
g_{therm}	0.03 K/m	Geothermal gradient
k_{ground}	0.4 W/(m·K)[2]	Thermal conductivity arid ground
ρ_{ground}	1800 kg/m^3	Density ground
C_{ground}	1000 J/kg/K	Heat capacity ground
T_0	308.15 K	Surface ground temperature (35^{0}C)
In_{fl}	313.15 K	Inflow temperature (40^{0}C)
r_{grout}	0.1 m	Radius grout
k_{grout}	2.4 W/(m·K)[3]	Conductivity grouting layer
C_{grout}	730 J/(kg·K)[3]	Heat capacity grouting layer
ρ_{grout}	1680 kg/m^3[3]	Density grout
gw_{depth}	47 m[4]	Groundwater depth
$\rho_{ground,sat}$	2000 kg/m^3[3]	Density saturated ground
$k_{ground,sat}$	2.7 W/(m·K)	Conductivity saturated ground/aquifer

(Anwt, n.d.)

[2] Thermal properties subsurface supplied by GFZ Helmholtz.

[3] (Drilling Products, n.d.)

[4] Measured on campus

9 RESULTS

9.1 Co-Axial Model in 2D

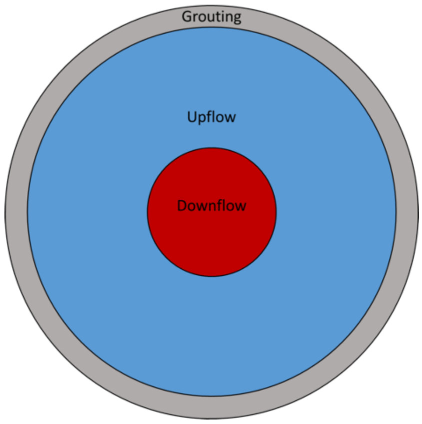

Figure 9-1: Co-Axial BHE with Grouting Layer

In the co-axial BHE the pipe for the downflow is in the pipe for the upflow. Only the upflow pipe is in contact with the subsurface. The rejected heat from the absorption cooler is transported by the water in the downflow pipe. The surface area of the upflow pipe is larger than that of the downflow pipe which causes the speed to decrease. The majority heat exchange takes place from the upflow pipe to the subsurface. The transferred thermal power is proportional to the mass flow rate.

Upflow

$$u = \frac{Q_{flow}}{\pi({r_{out}}^2 - {r_{in}}^2)} \quad [\text{m/s}] \quad (9.1)$$

Downflow

$$u = -\frac{Q_{flow}}{\pi {r_{in}}^2} \quad [\text{m/s}] \quad (9.2)$$

The heat transport that takes places between the borehole pipe and the ambient subsurface and within the pipes is the most challenging part for simulation. The equations of motion for the fluid are hardly solvable due to the large ratio of the radius of the pipe to its length ($r/l \approx 10^{-4}$) (P Oberdorfer et al., 2012). Therefore an approximation of the transversal heat transport of fluid flow in the pipe is used by taking the mean velocity and to calculate the heat transport using the heat equation. In the model the upflow and downflow are therefore considered to be a line heat source and are modelled in 1D.

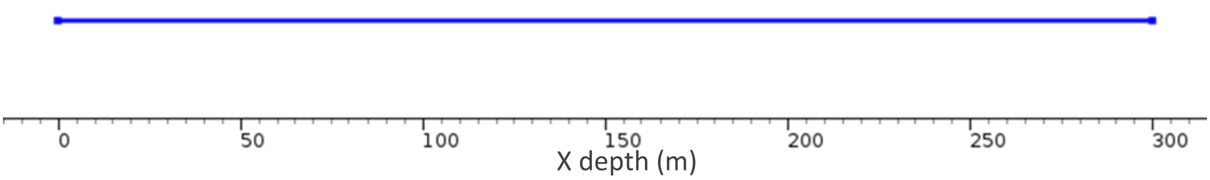

Figure 9-2: 1D Linesource (X is depth in m). Reversed, 300 is surface 0 is largest depth.

9.1.1 Linear Extrusion

The temperature connection between the upflow 1D linesource and the subsurface is done with a linear extrusion. In this case the upflow is the source and COMSOL connects the temperature of the upflow to the subsurface automatically.

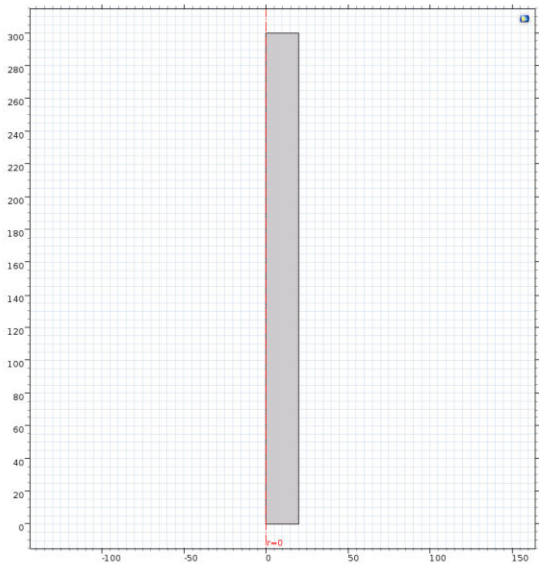

Figure 9-4: 2D Subsurface, connected to 1D linesource

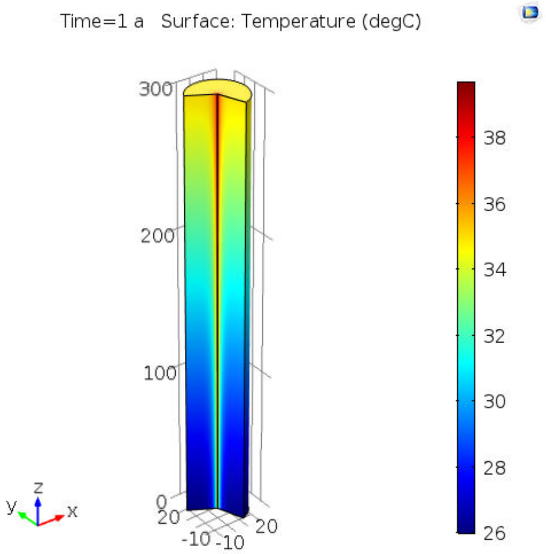

Figure 9-3: 2D Subsurface (depicted in 3D), connected to 1D linesource. Temperature impact (1 year).

9.1.2 Geothermal Gradient

The geothermal gradient is the difference in temperature with increasing depth. Usually the temperature increases with increasing depth, however according to data supplied by GFZ (Winterleitner, 2016), the temperature decreases in this case. This can be attributed to the unconventionally high surface temperature of Oman. Formula 9.3 describes *T,* the temperature at a specific depth, with T_0 as the surface temperature.

$$T = T_0 - g_{therm} \cdot (x_{\downarrow} - x) \qquad [\mathrm{K}] \qquad (9.3)$$

9.1.3 Heatflux and Heatsource

Upflow

The heatflux from 1D linesource (upflow) to the subsurface is done with a linear extrusion from the subsurface to the linesource. In this case linear extrusion connection acts as if the subsurface is the source for the heatflux. In reality the heatflux takes place from the BHE to the subsurface and therefore the heatflux becomes negative when calculating the heat source.

$$Q_0 = k(x_{\downarrow} - x_{ins})\Delta T - \frac{\vec{q}}{\frac{r_{out}}{2}} \qquad [\mathrm{W/m^3}] \qquad (9.4)$$

Where x is the depth of the borehole minus insulation (if this is used) and ΔT the temperature difference between the downflow and upflow.

The heatflux has to be divided by $\frac{r_{out}}{2}$ because the heatflux is originally considered from a linesource to the 2D subsurface. The heatflux in COMSOL is present over the surface of the BHE at every x. In the 1D it is only considered on the circumference of the BHE for every *X*. Therefore the circumference of the BHE has to be divided by the surface:

$$\frac{2\pi r}{\pi r^2} = \frac{2}{r} = \frac{1}{\frac{r_{out}}{2}} \qquad \text{[n.a.]} \quad (9.5)$$

The heatflux is modelled from the subsurface to the upflow, and not the other way around, because two linear extrusions with different variables in the same direction would cause errors in COMSOL. This is accounted for manually by making the heatflux negative.

Heatsource:

$$Q_0 = kx\Delta T \qquad [\mathrm{W/m^3}] \quad (9.6)$$

By taking the integral of the Heatflux over the entire BHE domain and multiplying it by the circumference of the borehole the amount of Watt that is rejected to the grouting material can be calculated:

$$Heatflux_{total} = 2\pi r_{out} \int_o^z \vec{q}\, dq \qquad [\mathrm{W}] \quad (9.7)$$

In Figure 9-5 this is done for the period of 1 year. As can be seen the heat rejection (W) after 1 year is approximately 1,400 W. It can be seen that the heat rejection decreases much more initially, creating an exponential effect. After 1 year the heat rejection appears to be much more stable.

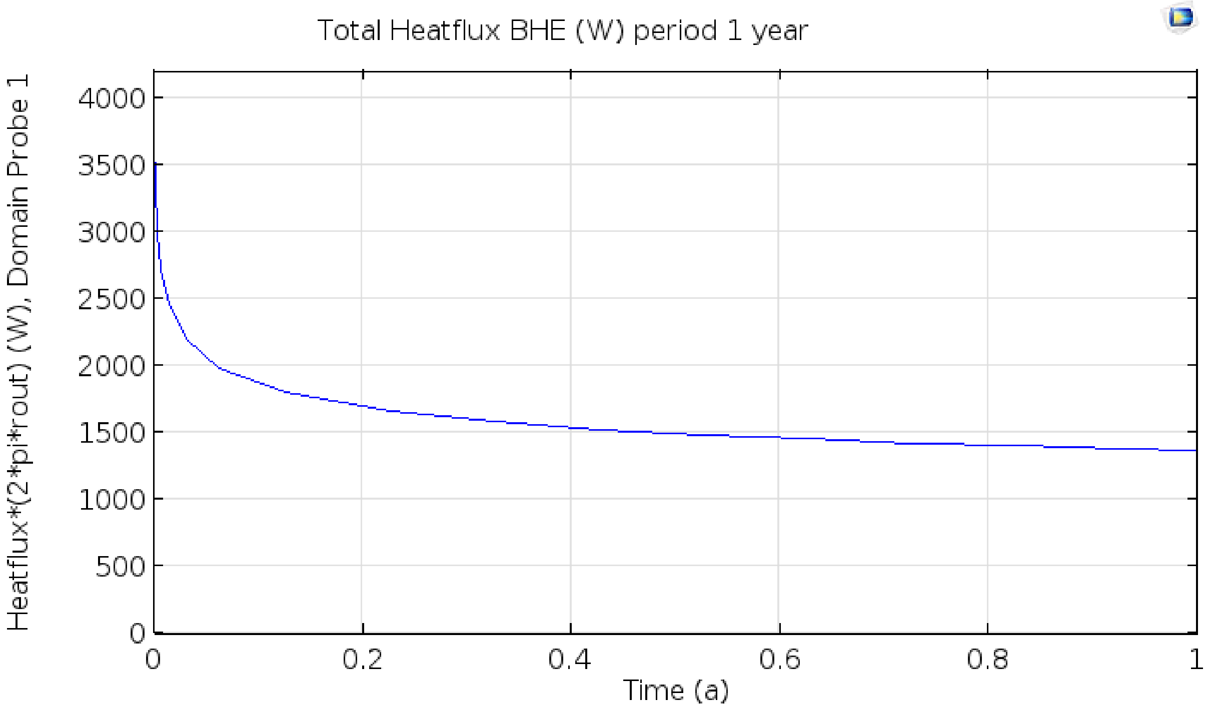

Figure 9-5: Heat rejection with a depth of 300 m. Period 1 year.

The decrease in heat rejection is caused by the increase of the temperature in the subsurface. The decreases the temperature difference between the subsurface and the BHE and therefore decreases the efficiency of the heat rejection.

The target heat rejection is 1,500 kW. In this basic example the target heat rejection is not achieved by more than a factor 1000. There are measures that can be taken to increase the heat rejection to the subsurface.

9.1.4 Grouting

To increase the thermal conductivity of the area surrounding the BHE a layer of grouting material can be added. This increases the amount of heat that can be exchanged between the BHE and the subsurface and therefore can increase the performance of the BHE. In Figure 9-6 it can be seen that after 1 year the heat rejection is nearly 2,000 Watt. This is approximately 600 Watt more than after 1 year without a grouting layer.

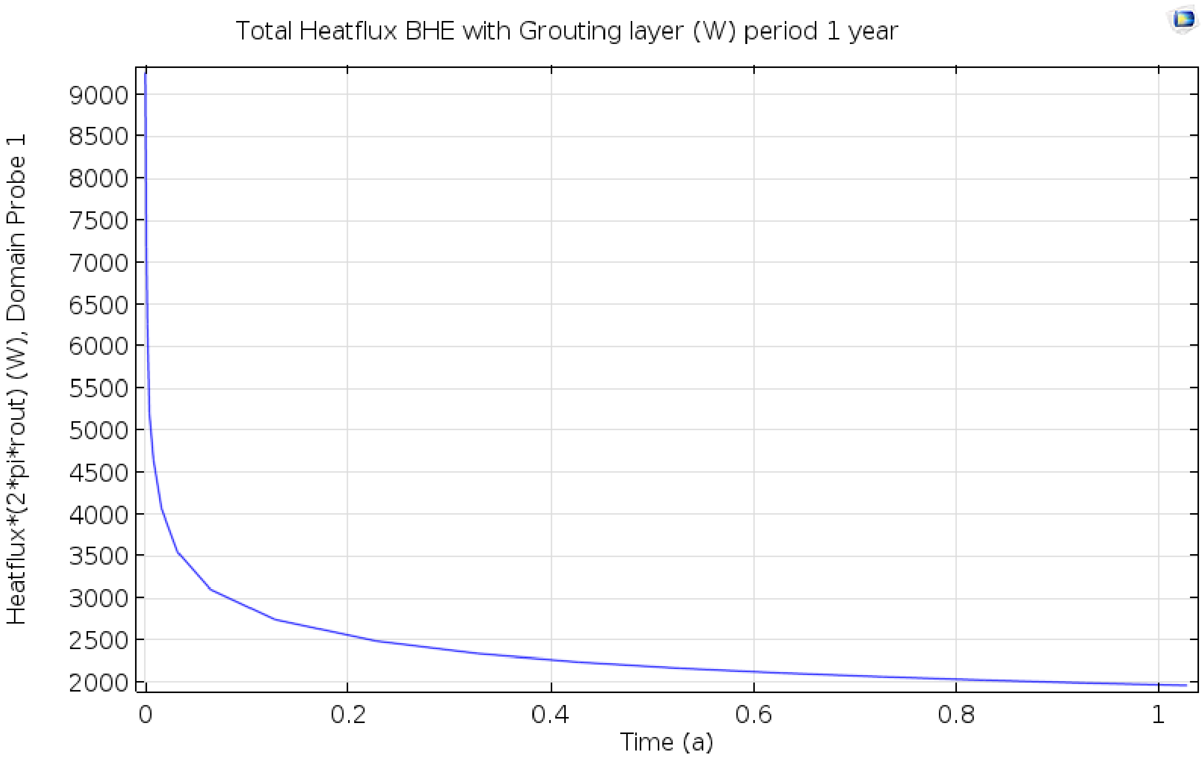

Figure 9-6: Heat rejection with a grouting layer with a depth of 300 m. Period 1 year.

9.1.5 Insulation

There is the option to insulate the downflow pipe of the BHE. This decreases (or in an example case, eliminates) the conduction between the internal and external pipes of the BHE. For lower fluid flow velocities within the BHE this can significantly impact the total exchange of heat between the pipes and the subsurface. For higher flow rates the impact of the insulation is limited.

9.1.6 Depth

Increasing the depth has a significant impact on the heat rejection by the BHE. By increasing the contact are of the BHE with the subsurface (and in this case the grouting layer) the heat exchange increases. With a depth of 600 meter and a grouting layer applied, the heat rejection is approximately 6,000 Watt after 1 year. This is approximately 4,000 Watt more than in the same situation with a depth of 300 meter.

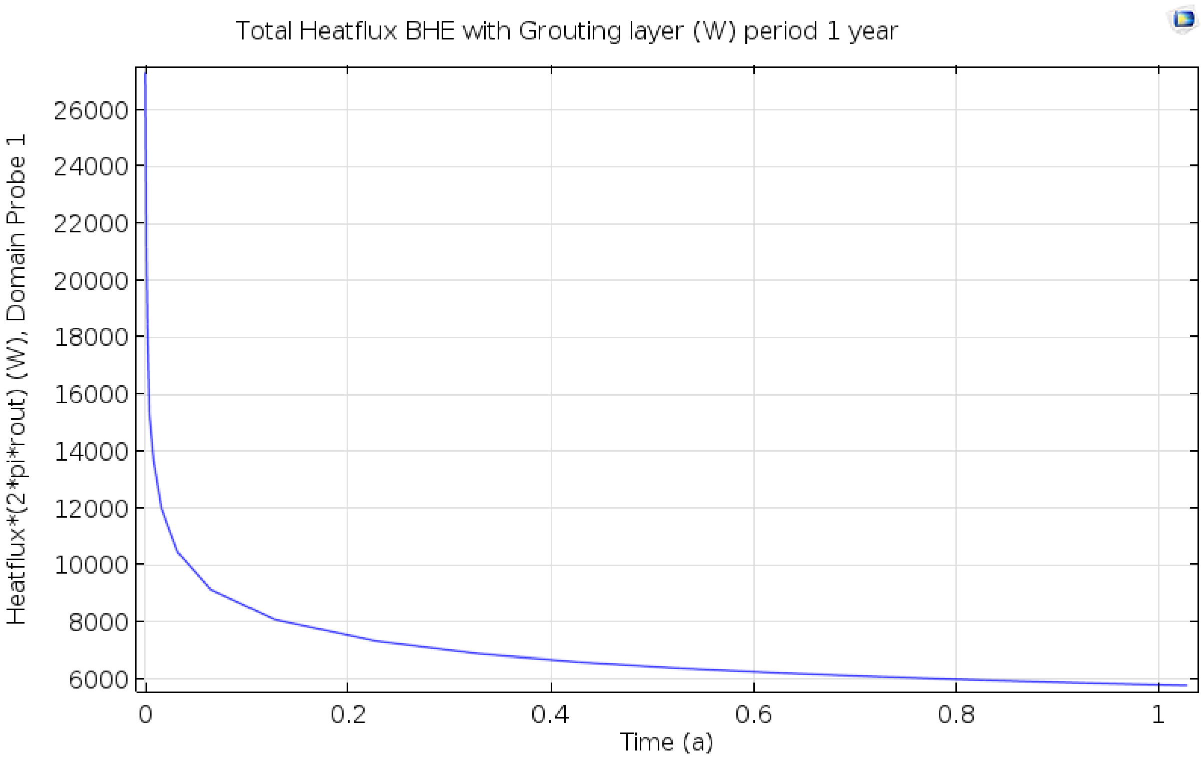

Figure 9-7: Heat rejection with a grouting layer with a depth of 600 m. Period 1 year.

Some variables have to be implemented to increase the validity of the model compared to reality.

9.1.7 Night and Day

Air-conditioning systems (in office buildings) generally do not run day and night. This is accounted for in the model by creating a sinusoidal function with a frequency of 24 hours or 86400 seconds and an amplitude of 0.5. The flow does not reverse and cannot become negative. This is accounted for by adding 0.5 to the function. By multiplying the function with the up- and downflow *u(t)*, the heat rejection during 24 hours is simulated.During night time there is no flow through the BHE and therefore only the limited amount of heat that is in the pipes during the night can be rejected. During daytime the flow through the pipes is at a maximum and therefore the heat rejection is maximal too.

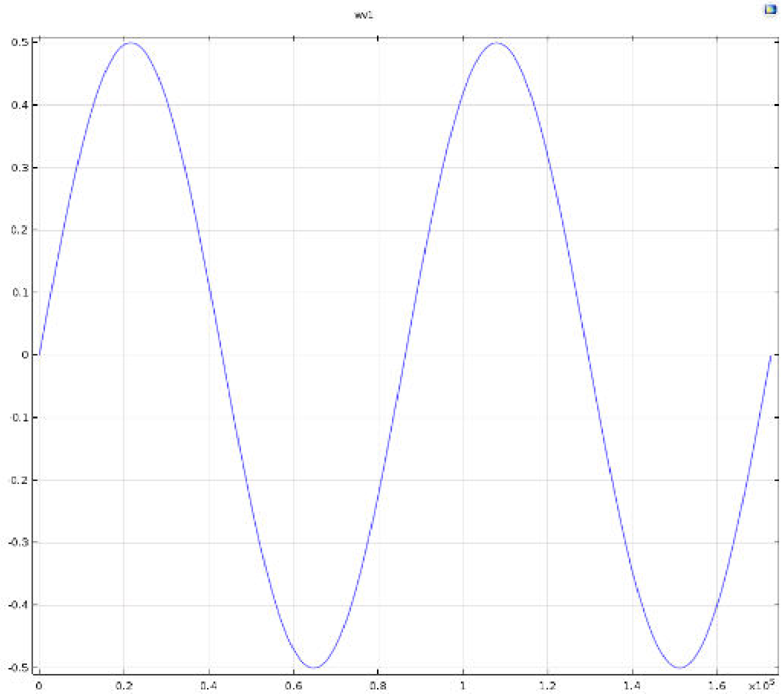

Figure 9-8: Sine function used to represent night and day flow

Upflow

$$u(t) = \frac{Q_{flow}}{\pi({r_{out}}^2 - {r_{in}}^2)} \cdot \left(0.5 + \sin\left(\frac{2\pi}{86400}t\right)\right) \qquad [m/s] \quad (9.8)$$

Downflow

$$u(t) = -\frac{Q_{flow}}{\pi {r_{in}}^2} \cdot \left(0.5 + \sin\left(\frac{2\pi}{86400}t\right)\right) \qquad [m/s] \quad (9.9)$$

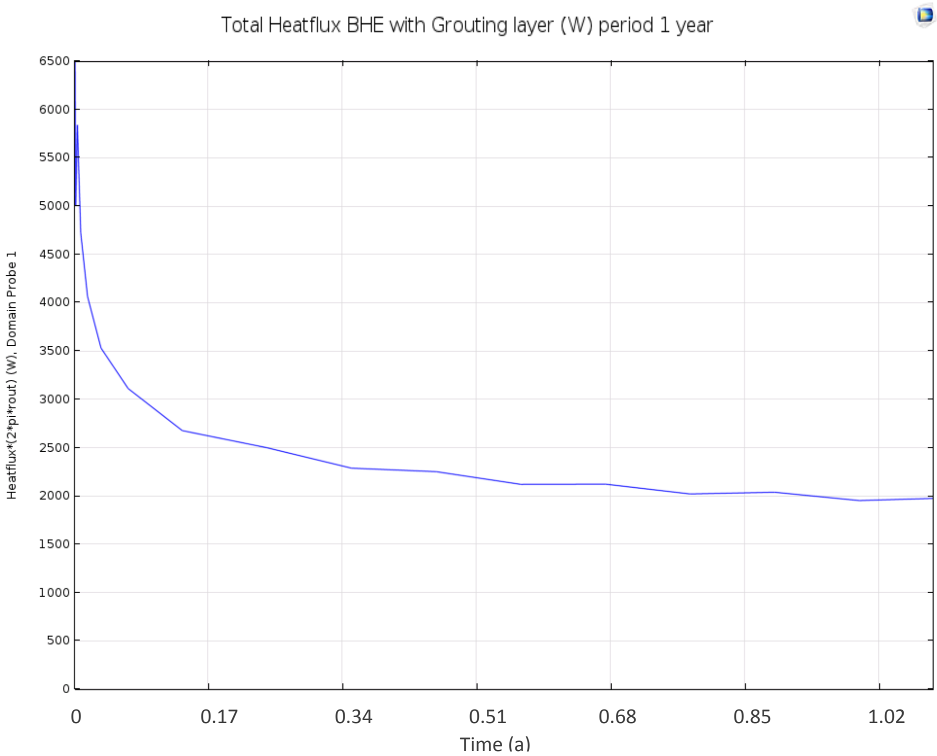

Figure 9-9: Heat rejection with night and day variability in flow. Period 1 year.

It appears from Figure 9-9, when compared to Figure 9-6 that the difference in heat rejection in the final situation after 1 year when taking night and day fluctuation into account is very limited. The heat rejection in both situations is approximately 2,000 W.

Temperature Increase

As explained earlier a gradual increase of the subsurface temperature is caused by the subsurface heat rejection. This leads to a decrease of the total heatflux. In Figure 9-10 the increase in temperature in the subsurface can be seen:

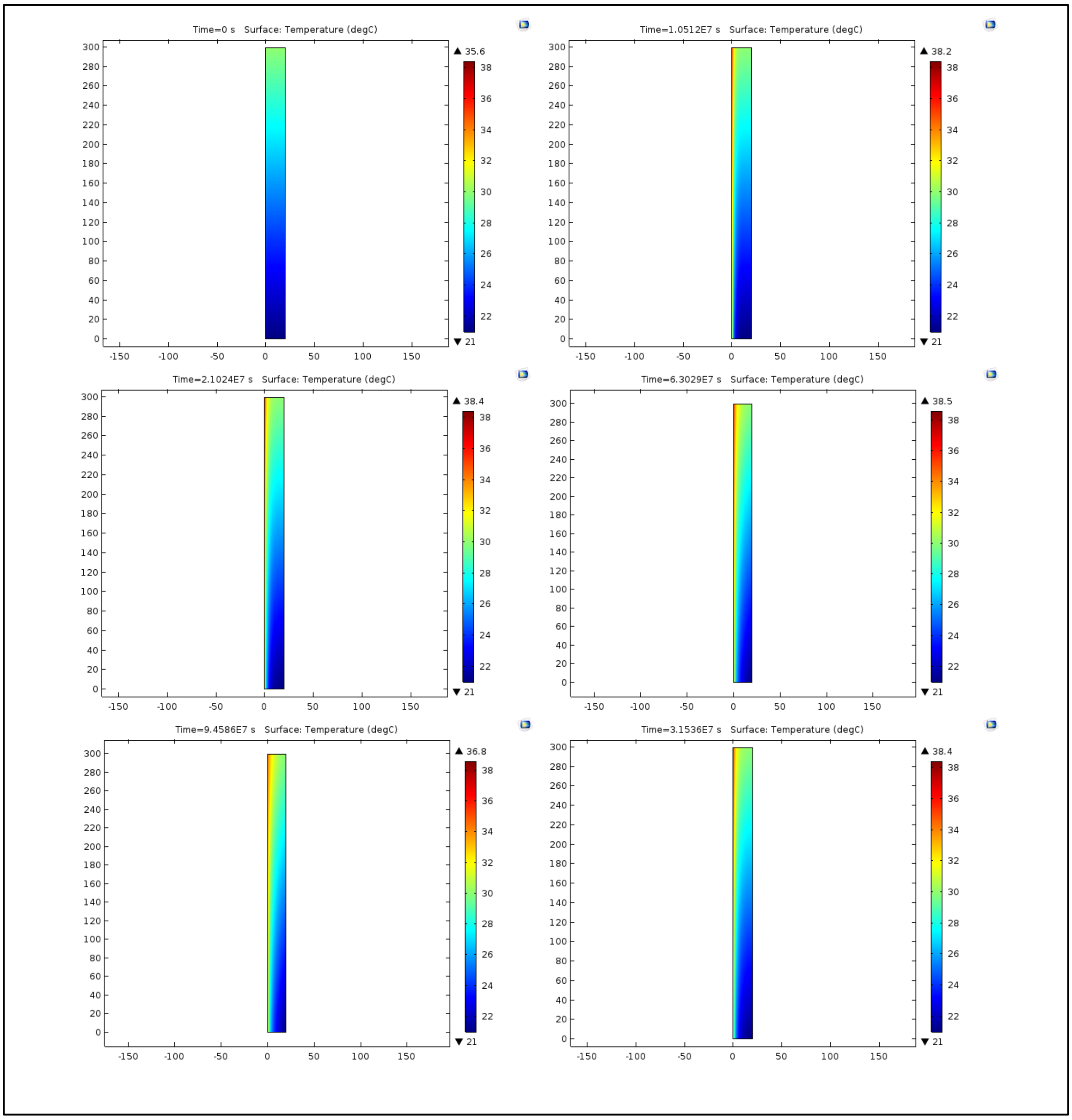

Figure 9-10: Increase of subsurface temperature. Period 3 year.

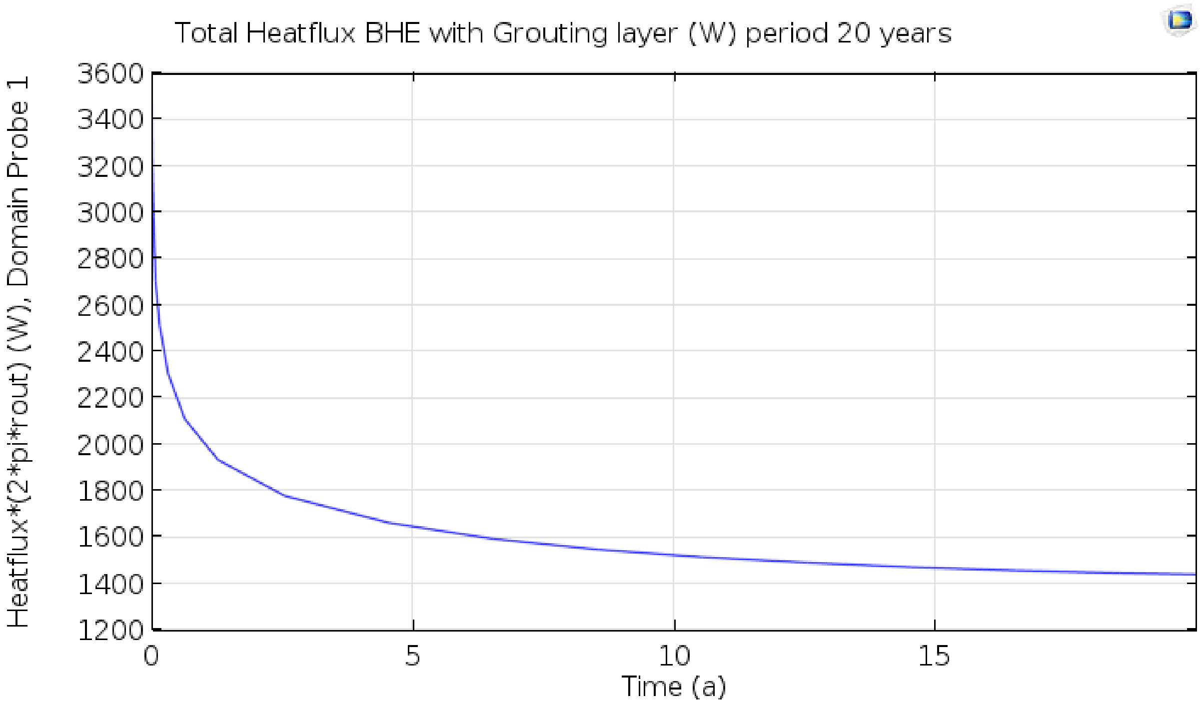

Figure 9-11: Heat rejection with a grouting layer with a depth of 300 m. Period 20 years.

The increase of subsurface temperature shown in Figure 9-10 for the short period of 3 years, has a large impact when evaluated over a longer period. As can be seen in Figure 9-11, the heat rejection over the period of 20 years shows a gradual decrease to around 1,400 W. In Figure 9-6 the graph shown after 1 year had a heat rejection of approximately 2,000 W.

9.1.8 Seasonal Variability

There is a large difference in the usage of air-conditioning throughout the year. In the summer the air-conditioning is running on full power, with the associated heat rejection and in the winter the air-conditioning is completely switched off. For sake of simplicity the transition period from summer to winter is not taken into account. The effect of switching the air-conditioning off in the winter is of interest.

The seasonal variability is modelled with Formula's 9.10 and 9.11:

Upflow

$$u(t) = \frac{Q_{flow}}{\pi({r_{out}}^2 - {r_{in}}^2)} \cdot \left(0.5 + \sin\left(\frac{2\pi}{86400}t\right)\right) \cdot \left(0.5 + \sin\left(\frac{2\pi}{86400} * 365t\right)\right) \quad \text{[m/s]} \quad (9.10)$$

Downflow

$$u(t) = -\frac{Q_{flow}}{\pi {r_{in}}^2} \cdot \left(0.5 + \sin\left(\frac{2\pi}{86400}t\right)\right) \cdot \left(0.5 + \sin\left(\frac{2\pi}{86400} * 365t\right)\right) \quad \text{[m/s]} \quad (9.11)$$

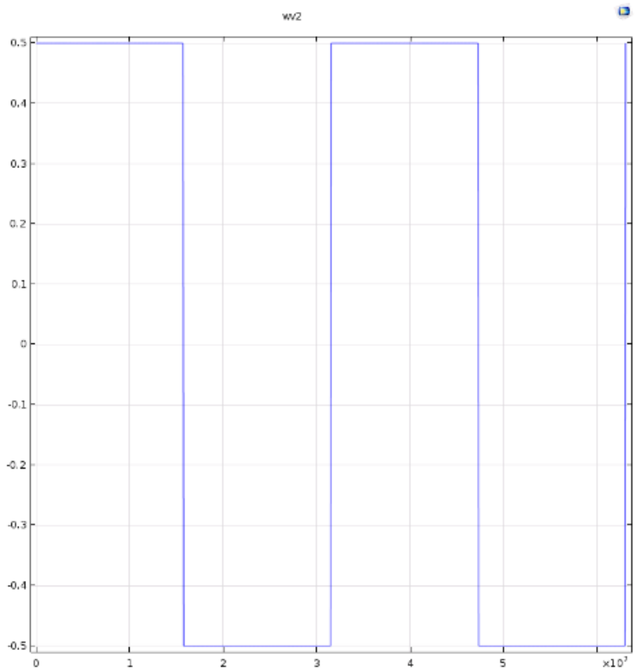

*Figure 9-12: Square function to simulate seasonal variability. Angular frequency: (2*pi)/(365*86400)*

After 6 months the air-conditioning is switched off and the heat rejection decreases to 0. Then after 12 months the air-conditioning is switched on again and the heat rejection increases accordingly. This is depicted in Figure 9-13:

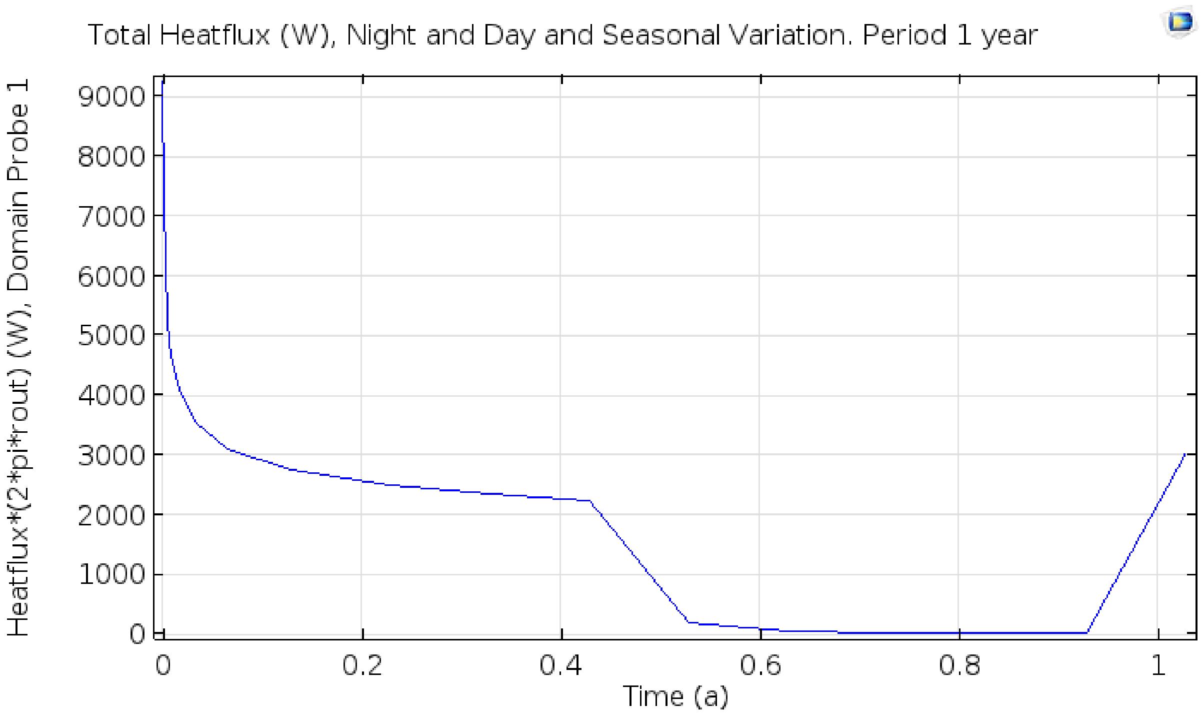

Figure 9-13: Impact of seasonal variability. Period 1 year.

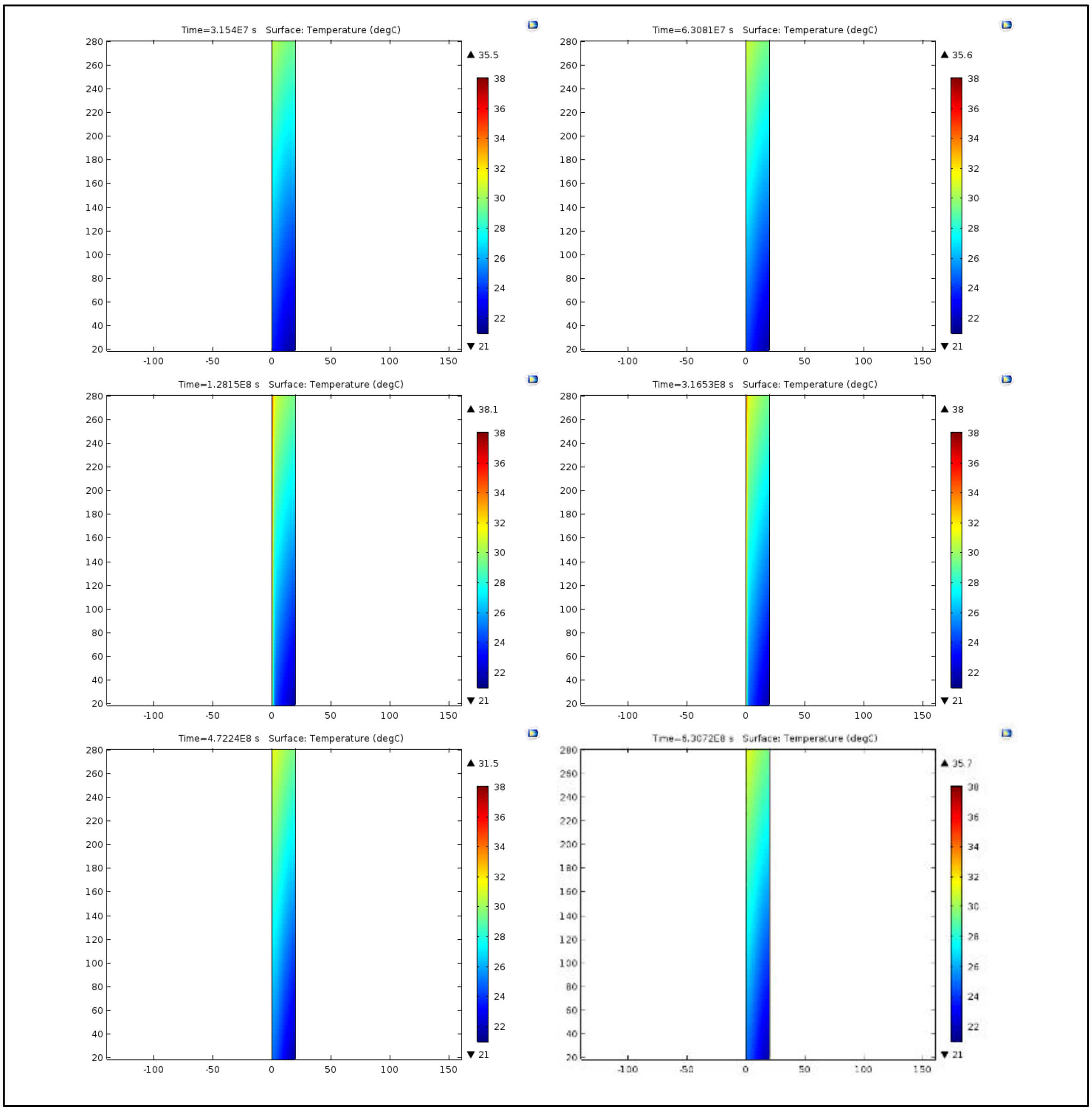

Figure 9-14: Increase of subsurface temperature. Period 20 years.

The increase of the subsurface temperature is much less when seasonal variation is accounted for. In Figure 9-14, the subsurface temperature increase is modelled for a period of 20 years. When compared to Figure 9-10, the temperature increase appears to be less than the situation after 3 years[2]. The heat that is rejected to the subsurface has time to disperse and the ground can cool down. This could be seen as recharging the cooling potential. The temperature difference between the subsurface and the BHE is then again larger after a period of non-heat rejection (winter).

[2] It must be taken into account that this is a snapshot and that the subsurface has cooled at the moment of this representation and therefore appears cooler than when an average would be taken.

This implies that the total heat rejection can be sustained over a longer period of time. When compared to Figure 9-11, it can be seen that the heat rejection after 20 years without taking seasonal variation into account, resulted in a heat rejection of approximately 1,400 W. In the case of seasonal variation (Figure 9-15), the heat rejection after the same amount of time is approximately 1,700 W.

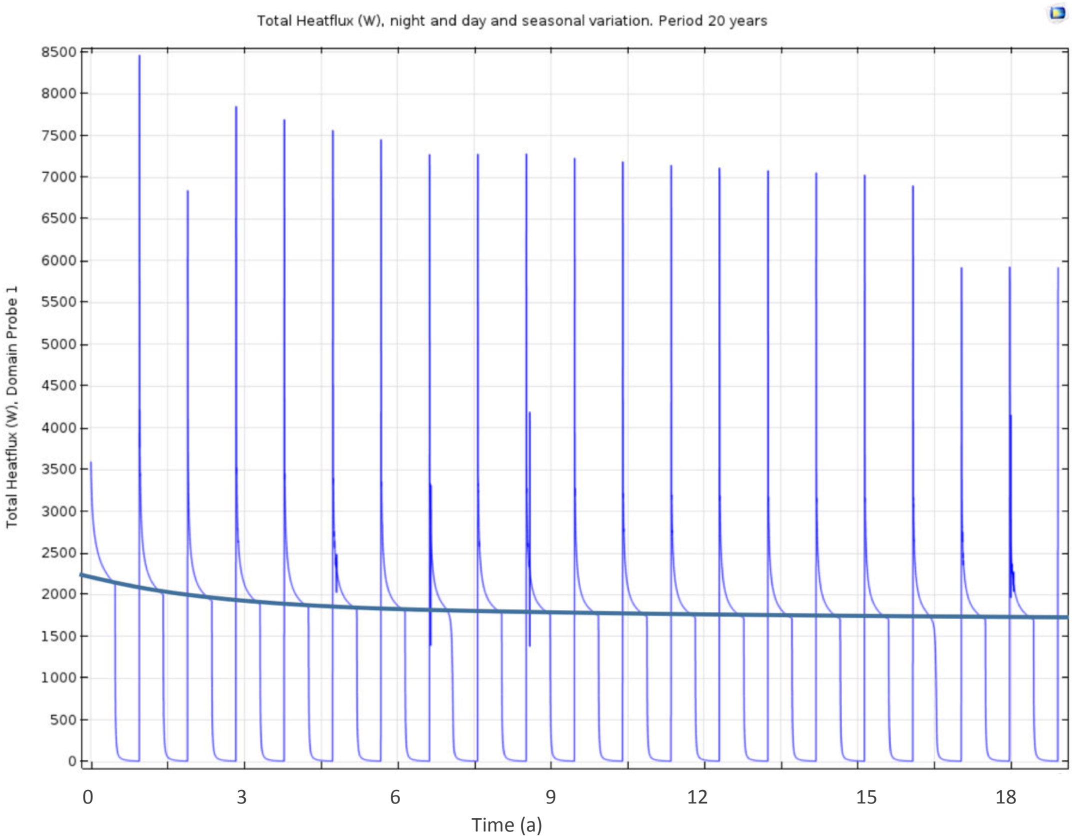

Figure 9-15: Impact of seasonal variability. Period 20 years.

9.2 Co-Axial Model in 3D

To create the same Co-Axial model in 3D it is necessary to write a new 3D model. Some elements can be used in both models. There are however some different techniques applied to the new model. This can result in inconsistencies between the two models.

Again the up- and downflow are modelled as a linesource. Transferring the heatflux to the subsurface is done with a Linear Projection (9.2.2).

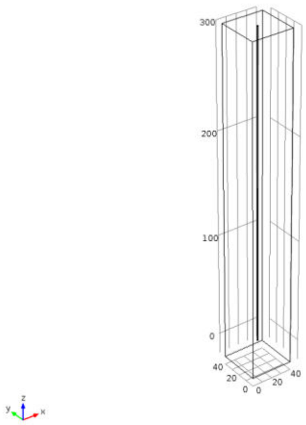

Figure 9-16: BHE modelled as linesource in 3D.

9.2.1 General Extrusion

The general extrusion has the same function as a linear extrusion (9.1.1) however, can be used from a 1D linesource to a 2D or 3D source. Therefore the general extrusion is a useful tool to link the temperature from the linesource to the subsurface.

9.2.2 Linear Projection

To calculate the total heatflux from the BHE (upflow) to the subsurface, a linear projection operator can be used to integrate the heatflux over the circumference of the borehole cylinder. Since the upflow is a linesource modelled in 1D, COMSOL does not recognize any contact between the pipe for the upflow and the subsurface. A projection of the total heatflux to the linesource is therefore a useful method. The cylinder surrounding the linesource is cut out of the subsurface. The cut out cylinder is divided in two halves. Both halves are considered as a surface that projects on the linesource.

The linear projection of the heatflux from the surface to BHE is used to calculate the heatflux from the BHE to the subsurface:

$$q_{tot}(z) = \int_0^{2\pi r} q\,(z, r) dr \tag{9.12}$$

The points in the 3D model are connected to the line source in 1D and COMSOL calculates the heatflux from the subsurface to the line source. As explained earlier the heatflux is therefore indicated as a negative value, because the direction of the actual heatflux is from the BHE to the subsurface. The direction of the heatflow is dependent on the temperature difference and the BHE has a higher temperature than the subsurface.

The absolute values of the heatflux in the X and Y direction have to be used, otherwise the heat fluxes opposite of each other cancel each other out Figure 9-17.

Both halves of the cut out cylinder have an X and Y component of the heatflux. This leads to two (vectors) heatfluxes:

Heatflux 1:

$$\vec{q}_1 = comp1.linproj1\big(abs(xf)\big) + comp1.linproj1(abs(yf)) \quad \text{[W/m]} \quad (9.13)$$

Heatflux2:

$$\vec{q}_2 = comp1.linproj2\big(abs(xf)\big) + comp1.linproj2(abs(yf)) \quad \text{[W/m]} \quad (9.14)$$

Where comp1 stands for the component of the model that is considered, linproj is the linear projection code and abs(xf) and abs(yf) stand for the absolute values of the x- and y component of the heatfluxes.

This leads to the heat source formula:

$$Q_0 = k(x_{\downarrow} - x_{ins})\Delta T - \frac{(\vec{q}_1 + \vec{q}_2)}{\pi r_{out}^2} \quad \text{[W/m}^3\text{]} \quad (9.15)$$

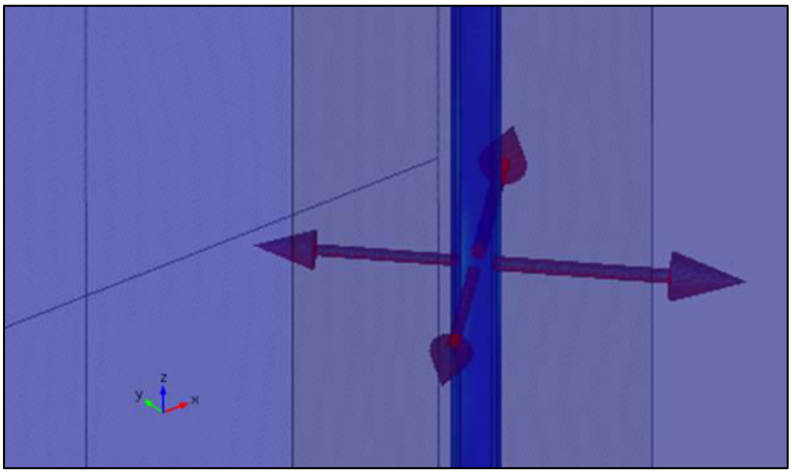

Figure 9-17: Heatfluxes in x, -x, y and -y direction would cancel each other out if the absolute values were not taken.

To calculate the total heatflux, the integral over the domain of the BHE is taken.

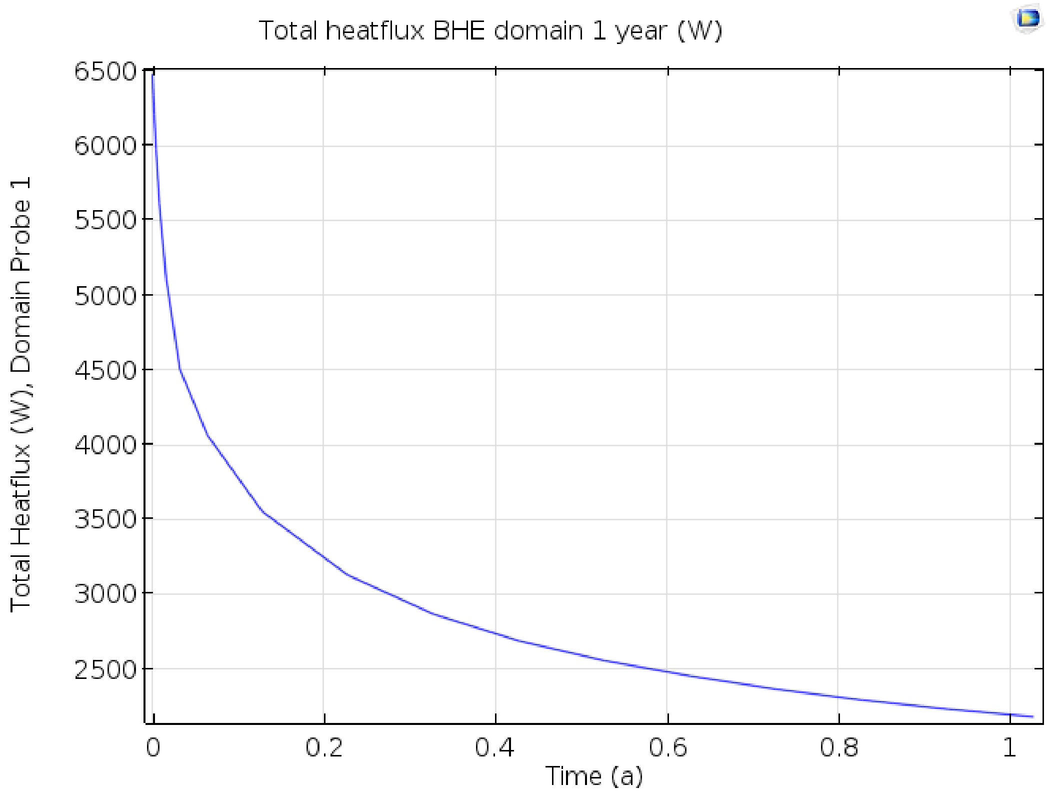

Figure 9-18: Heat rejection with a depth of 300 m. Period 1 year.

The decrease in heat rejection over time in Figure 9-18 is caused by the increase of the subsurface temperature, decrease in difference between BHE and subsurface temperature and related decrease in heat rejection efficiency (as in Figure 9-5). As mentioned there is a difference between the result in 2D standard situation and the 3D standard situation.

Evaluated over 20 years the heat rejection is approximately 1,700 W (Figure 9-19):

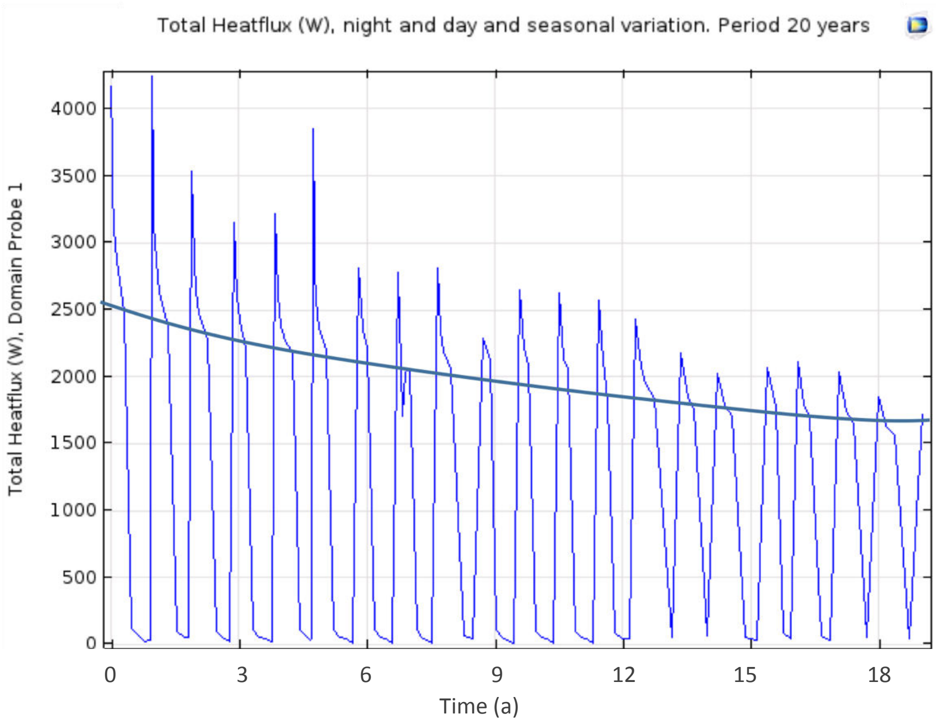

Figure 9-19: Heat rejection. Period 20 years.

9.2.3 Ground Water

In the measurements done on the GUtech campus the groundwater level was at 47 meter depth. The saturated ground has a much higher conductivity ($k_{sat,ground}$= 2.54 W/(m·K)) than the arid subsurface (k_{ground}= 0.4 W/(m·K)). The groundwater therefore substantially increases the amount of heat that can be rejected to the subsurface.

In Figure 9-20 the temperature distribution after 1 year is visible. Compared to Figure 9-4 the temperature is higher, wider spread and a transition from the arid to the saturated layer is visible.

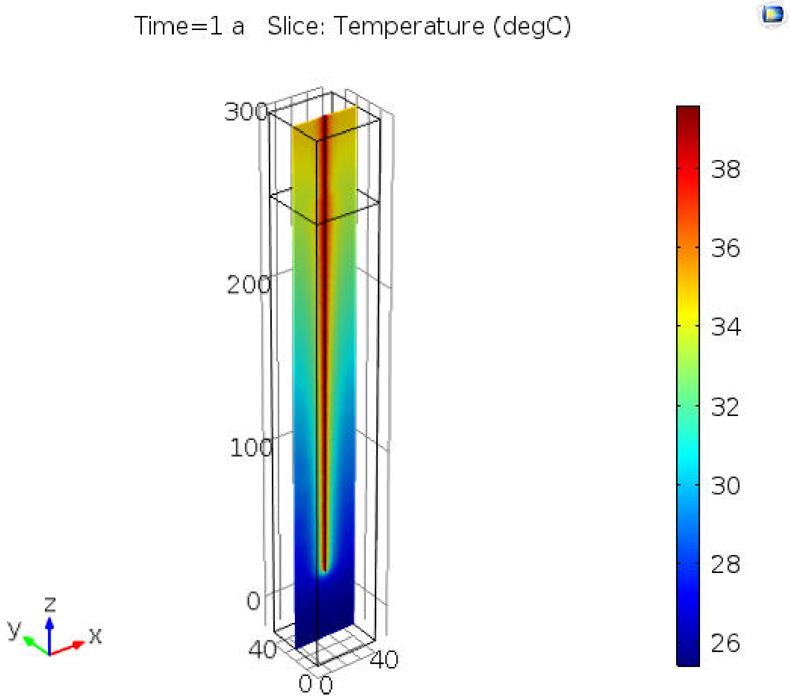

Figure 9-20: Temperature distribution with a BHE depth of 300 m. Ground water level at 47 m depth. (Time 1 year).

The heat flux to the subsurface in Figure 9-21 can be seen to increase with depth. This is caused by the high difference in temperature between the subsurface and the BHE. This is the result of the BHE water coming into contact with the subsurface, after exiting the inner pipe, at the greatest depth,

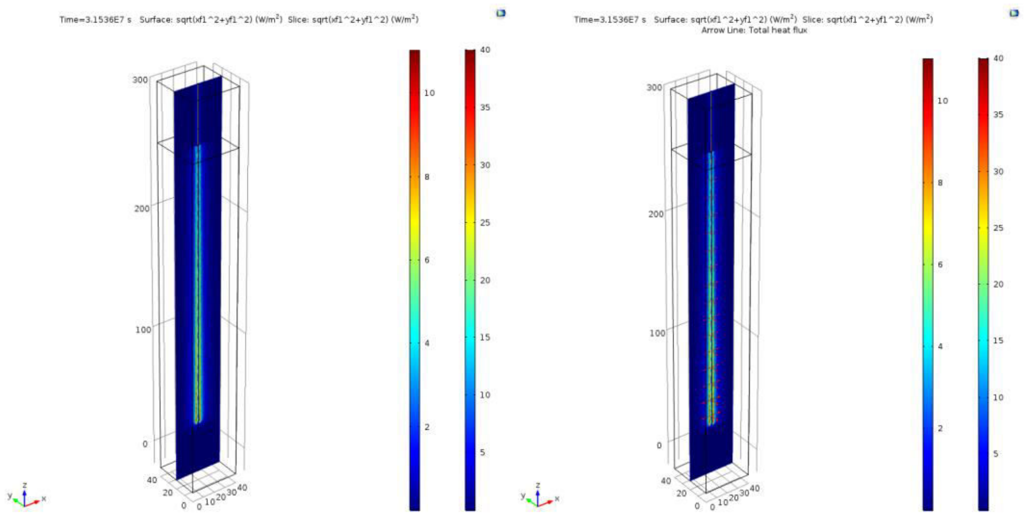

Figure 9-21: 2 BHEs with Heatflux in Arid (top segment) and Saturated (bottom segment) Subsurface (time 1 year)

and the temperature of the subsurface at the greatest depth being the lowest of the column.

The heat rejection to the subsurface is approximately 9,500 W after 1 year. Incorporating the saturated layer into the model with the higher conductivity has lead to a higher amount of rejected heat.

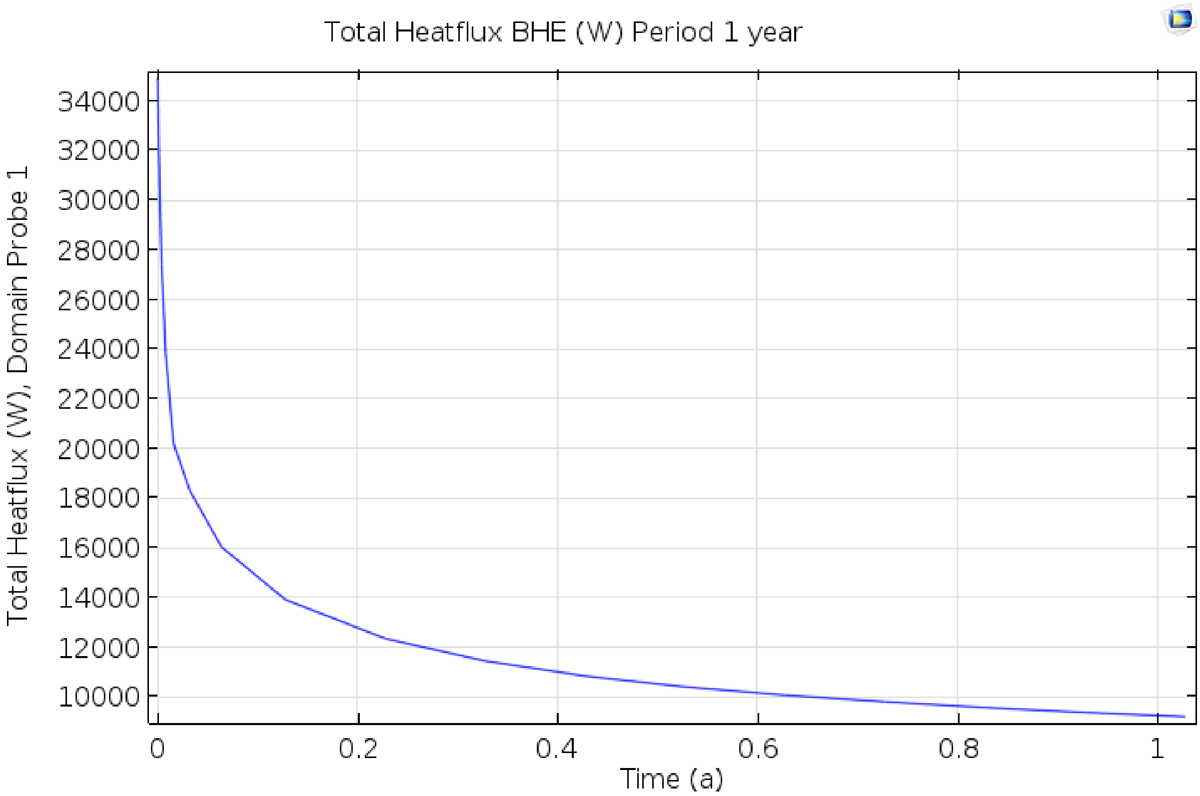

Figure 9-22: Heat rejection with 300m BHE. Period 1 year.

9.2.4 Ground Water Flow

When groundwater flow occurs the heat that is rejected to the subsurface is transported away from the BHE through convection. This implies that the temperature difference between the BHE and the subsurface is less impacted by the heat rejection over time and that the efficiency of heat rejection can be better maintained. The occurrence of groundwater flow can significantly improve the performance of the BHE. In Figure 9-23 the groundwater flow has a velocity of $1 \cdot 10^{-5}$ m/s and flows in the *X* direction.

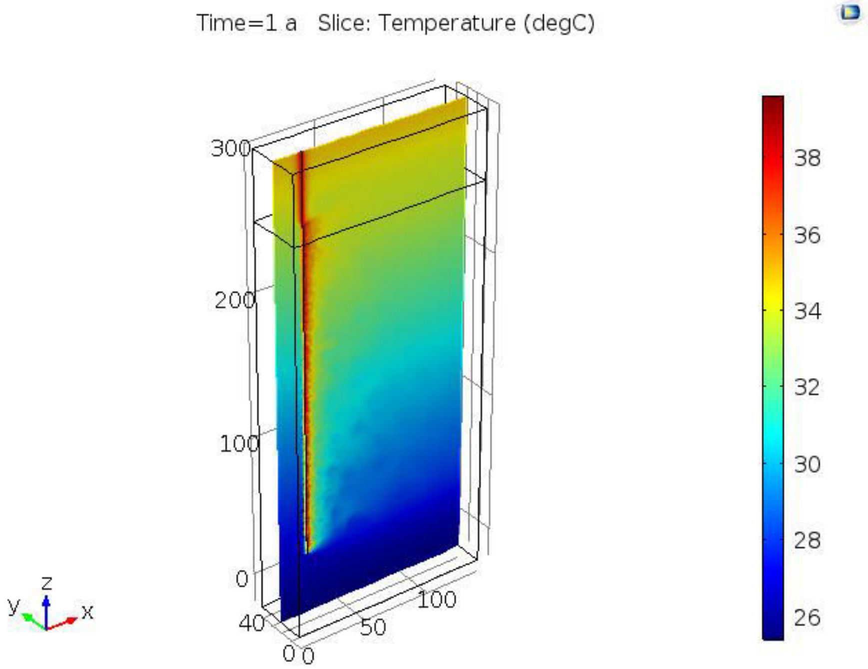

Figure 9-23: Temperature distribution in the subsurface, BHE 300 m depth with groundwater flow $1 \cdot 10^{-5}$ m/s. (time 1 year).

The temperature increase due to heat rejection from the BHE to the subsurface is depicted in Figure 9-23. The plume from the BHE (in the flow direction) is an indication that the amount of heat rejected to the subsurface is higher than in Figure 9-20, without groundwater flow.

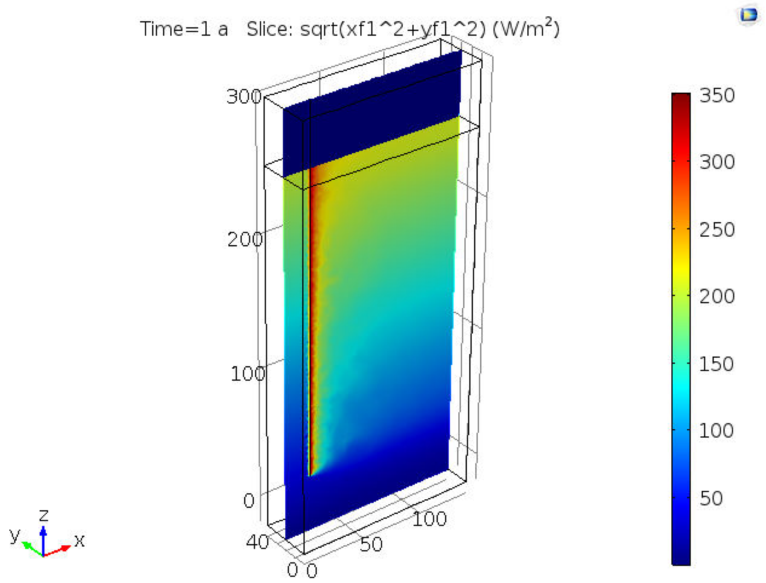

Figure 9-24: Heat rejection from the BHE 300 m to the subsurface. (time 1 year).

The heat rejection after 1 year in Figure 9-25 is approximately 2,000 kW. The subsurface groundwater has a significant impact on the subsurface heat rejection, increasing the performance of the BHE with more than a factor 1,000 from the initial modelling attempts.

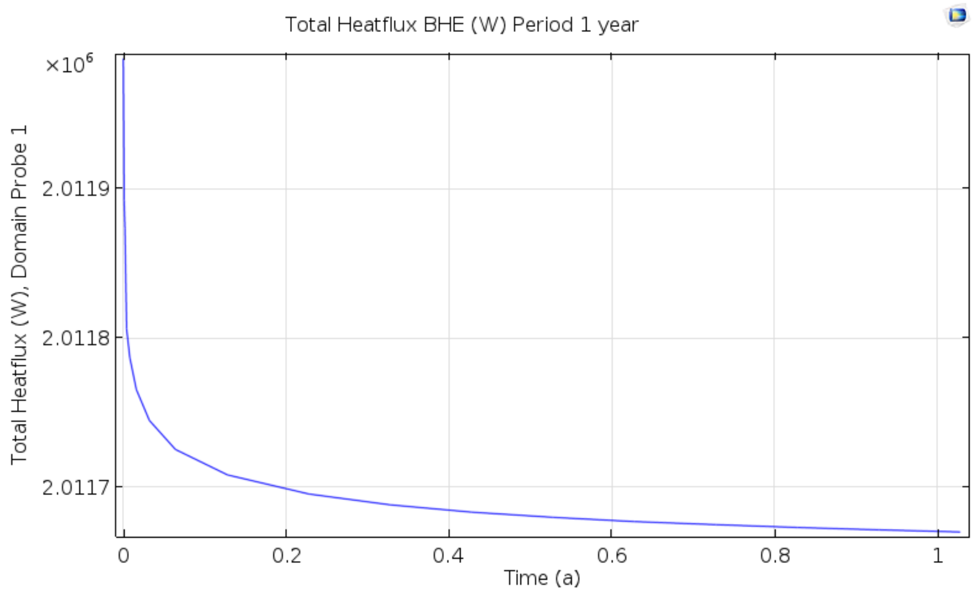

Figure 9-25: Heat rejection from BHE 300 m, with groundwater flow. Period 1 year.

In Figure 9-26 the temperature development from the downflow to the upflow is, with an inflow temperature of 40^{0}C, is depicted. Here one can see that during the downflow the temperature decrease is minimal. The upflow temperature decrease is much larger and steepest around the turning point (0 m). The temperature then decreases gradually until the arid top layer is reached. Here the temperature increases a little again, due to higher temperature of the inner (downflow) tube and the low conductivity of the subsurface.

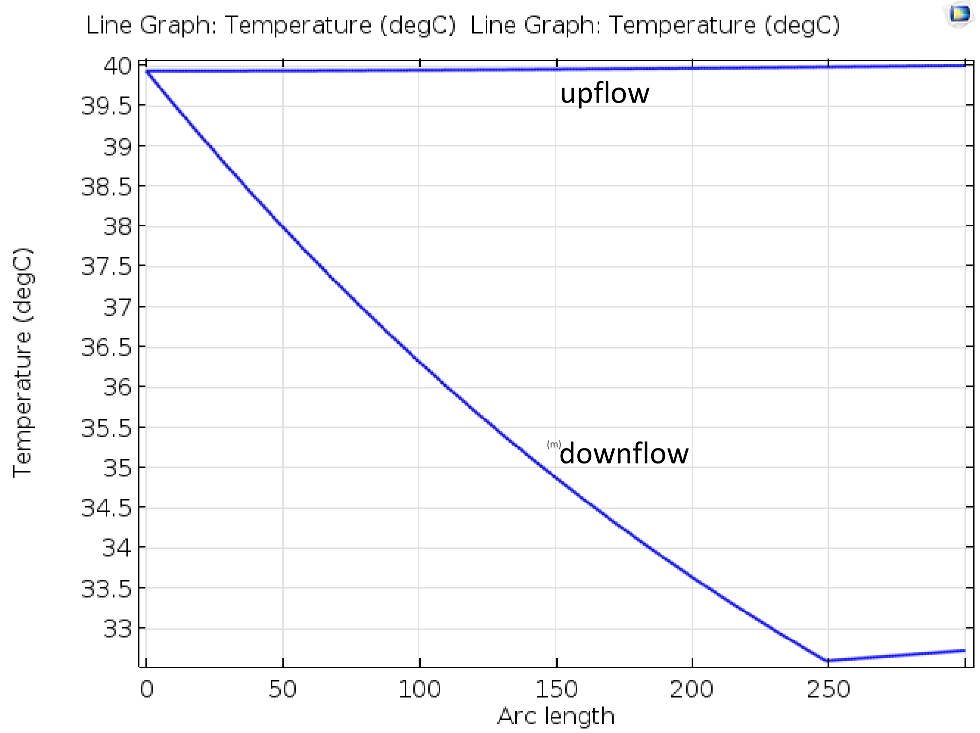

Figure 9-26: Temperature in up- and downflow pipes.

10 SENSITIVITY ANALYSIS

10.1 Parametric Sweep

To evaluate which combinations of parameters result in the largest potential heat rejection, a parametric sweep was performed. The parametric sweep is a study node that enables finding the optimal solution to time-dependent partial differential equations, when parameters of choice are varied.

In this case the depth of the BHE and the flow volume through the BHE are the parameters that were be varied. In Figure 10-1 it is visible that there is a significant rise in heat rejection when compared to Figure 9-25. In Figure 10-2 the heatfluxes for a flow volume of 50, 150 and 250 m^3/h and 300, 450 and 600 meter depth are depicted. It can be seen that the largest impact is from an increase in depth. The Impact of an increase of flow velocity is relatively minimal.

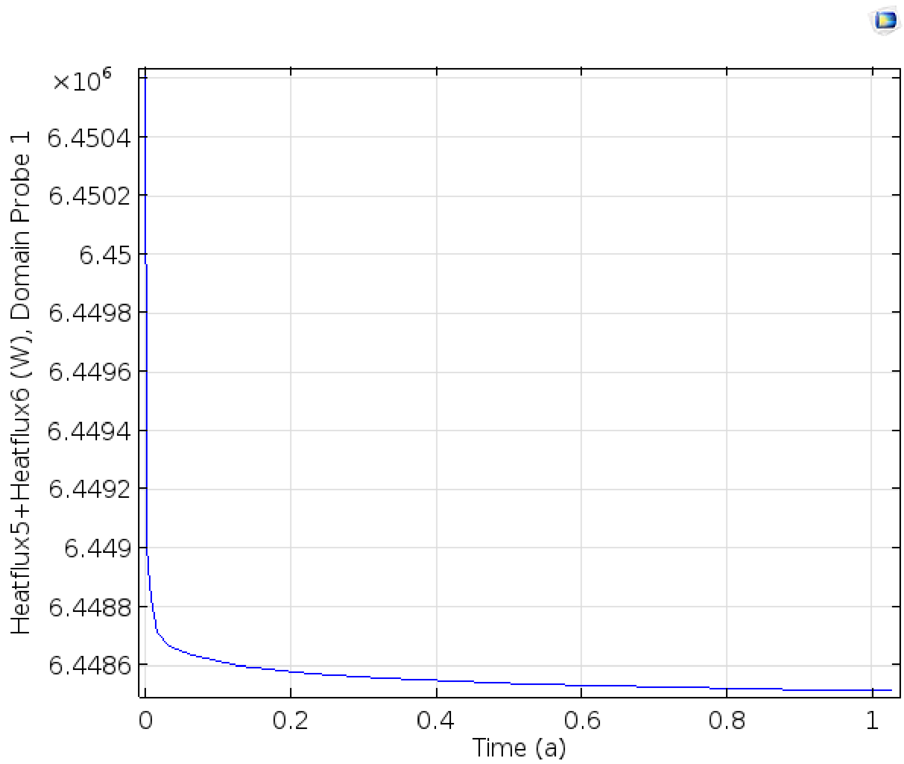

Figure 10-1: Heatflux 250 m^3/h, BHE depth 600 m. Period 1 Year.

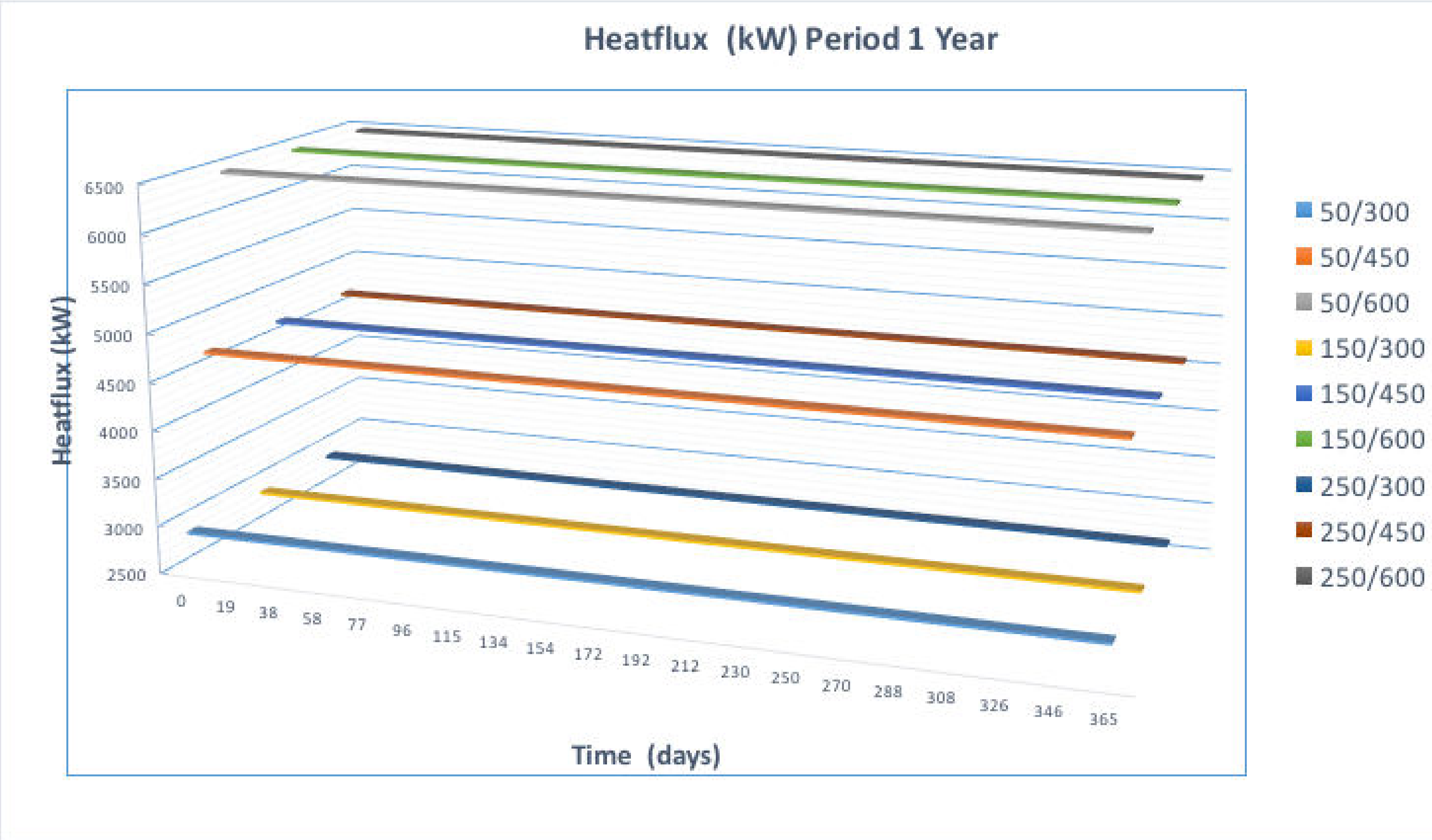

Figure 10-2: Accumulated Graph of Heatfluxes, different flow velocities and depths.

11 DISCUSSION

11.1 Limitations & Challenges

In modelling the subsurface there are some facts that have to be taken into consideration as they pose limitations on or challenges to the correctness of the model.

11.1.1 Heterogeneity, Nonlinearity & Uncertainty

Geothermal reservoirs tend to be very heterogeneous. To a large extent geomechanical properties, fluid flow and transport are determined by fractures (Huenges, 2010). For simplicity it can be assumed that the subsurface is homogeneous or exists of chosen stratigraphic layers, without anomalies.

Large imposed changes of the thermodynamic variables like pressure, temperature and stress, cause fluid and rock properties to behave nonlinearly (Huenges, 2010). In reality this leads to local differences in e.g. thermal conductivity and heat capacity.

The information on geothermal reservoirs is very minimal due to limited availability of data on material properties from few measurements.

11.1.2 Measurements

In May a borehole temperature measurement apparatus was supposed to be available (from the research group in Germany) that would enable accurate down-hole analysis. This was delayed until September, therefore an estimation of the subsurface temperatures was made based on previous knowledge

It is assumed that the temperature decreases with depth. This is based on data supplied by Winterleitner (2016). Normally temperature increases with depth. A reason that this could be the other way around is due to the high surface temperatures in Oman. After a certain depth the temperature will increase again. Here it is assumed that the BHE doesn't go that deep, therefore only the decreasing temperature formula applies.

11.1.3 Temperature Dependence

In most numerical simulations the fact that all involved parameters are functions of the temperature, is neglected. Taking the bi-directional coupling of the equations into consideration would complicate the model and is expected to have limited influence on the correctness (Phillip Oberdorfer, 2014).

11.1.4 Non-Constant Heat Injection

The necessity for cooling varies per time and season. The associated heat rejection is therefore variable and could vary greatly between e.g. summer and winter. An increase in the subsurface temperature as impact of the heat rejection will negatively influence the efficiency of the absorption cooler. The seasonal variation of heat rejection will allow the subsurface to (partially) restore towards the original state and potentially increase the efficiency in periods of increased heat rejection.

On a shorter timescale there is also an expected intensity difference between the heat rejection during day and night. Besides potential efficiency increase, the non-constant heat injection forms a challenge to the correctness of the model as it more difficult to account for this variability. In reality the heat rejection will never be constant and therefore this has to be taken into consideration for the correctness of the model. In this model the heat rejection for day and night is considered a sinusoidal function and for summer and winter heat rejection an on or off function. This is a highly simplistic representation.

11.2 General Predictions

Energy saving technologies generally tend to exhibit shortcomings comparing predicted performance with real life performance. This inconsistency is caused by testing technologies under laboratory (ideal) conditions or inhibited hopes of producers and designers for a certain performance. Amongst other causes of these shortcomings, the quality of the installation can be inadequate and climatic conditions can be unpredictable and unstable (Sweetnam et al., 2014)**.**

11.3 Model

The model is a simplification of reality and therefore has left some naturally occurring phenomena out of consideration.

Ground level temperature is kept constant at the surface throughout the year. In Oman the temperature is generally much higher in the summer than in the winter. The impact overall is limited due to the relatively large depth of the BHE compared to the seasonal variation depth. However, in a more complete model, this variation could be accounted for.

11.3.1 Flow Conditions

According to Oberdorfer et al. (2012) the heat exchange between the pipe and the subsurface is mainly controlled by the flow conditions in the pipe, therefore the effective thermal conductivity of the pipe walls has to be calculated. The heat transfer from the fluid into the pipe and the thermal resistance of the pipe wall must be taken into account.

In my model I use a line source for the up- and down flow and neglect the potential impact of thermal resistance on the wall of the pipe and the impact of other flow conditions.

11.3.2 Absolute Values

By modelling the linear projection of the cylinder surrounding the BHE in 3D, the negative and the positive fluxes would cancel each other out. This is caused by the fluxes being more or less the same size coming from both the positive and the negative side (x, -x and y, -y) of the BHE. This would result in a deviation when attempting to display the total heatflux. Therefore the absolute values of the fluxes are used to calculate the total heatflux.

11.3.3 Inconsistencies

There are some inconsistencies between the 2D and 3D model. It could be rounding errors, usage of a different, internal connections in the models or something that is done slightly different in the simulation process.

For validation of BHE models exact data on the thermal properties or data on comparable test sites is necessary. This data is hardly available and thus forms a challenge for the correctness of any modelling attempt.

In the 2D model grouting is used. In the 3D model grouting has not been used. The two models are compared without explicit consideration of the impact grouting might have. This does make a difference.

11.4 Performance Aspect

Geothermal energy systems should not be sized according to the maximum required cooling load for a specific building. 60% to 70% of the maximum demand load should be the capacity of the cooling system for the most effective solution. The peak load can be accommodated by a supplementary cooling system (Energuide, 2004). With the cooling requirement in Oman this remains disputable, as the system would be switched off during winter. Only the period in which the system is switched on should be taken into account, otherwise the installed capacity would be insufficient to run the cooling system efficiently. Most of the runtime the absorption cooler would then have to be supplemented with conventional cooling systems, offsetting the positive energy reduction effect.

According to a Canadian research (Energuide, 2004) usually about 80 to 110 meter of piping is necessary to produce 3.5 kW of heat pump capacity. The conditions to which this applies are not stated clearly, but in this research the achieved heat rejection is much higher.The conditions to which this applies in Canada are very different from those in Oman. The installation in Canada is used for heating mainly and the system in this research for heat rejection.

From the Parametric Sweep (10.1) it appeared that the increase of depth has the most significant impact on the heat rejection. Increasing the depth of the BHE comes with an increase in construction costs. Whether to increase the BHE depth can be considered in a cost benefit analysis.

11.5 Regulations

Even though there are strict regulations protecting Oman’s water resources published in the Royal Decree in 1989, utilization of the resources is likely in the interest of the Sultanate. Using an aquifer for subsurface heat rejection aligns with the national target to move to renewable energy resources. Therefore after careful assessment of the environmental impacts, a deeper, or open source geothermal system could potentially be agreed.

11.6 Further research

In order to make a good prediction about the viability of the entire system, a lifecycle analysis should be done. The ratio of used materials and energy consumption during production and installation of the system has to be evaluated against the potential energy reduction the system would deliver.

12 CONCLUSION

The target heat rejection to drive the absorption cooling process efficiently is 1,500 kW. Due to the high ambient air temperature conventional heat rejection to the air is not efficient enough to run the absorption cooling process. Therefore, in this research heat rejection to the subsurface is investigated. The literature segment consists of research into the absorption cooling system and into comparable environments. In COMSOL Multiphysics several models have been made, gradually incorporating more aspects that increase the reliability of the model.

Is absorption cooling possible for the climatic conditions in Oman?

With the current parameters and variables taken into account, subsurface heat rejection exceeds the target heat rejection of 1,500 kW. The subsurface heat rejection in Figure 9-25 is approximately 2,000 kW after the runtime of 1 year. As in previous examples, the heat rejection decreases after a longer period of time. However, it has been shown that this decrease is fairly limited once seasonal variability is taken into account. Therefore, focussing on the subsurface heat rejection, it is expected that absorption cooling is possible for the climatic conditions of Oman.

Wat is the maximum obtainable heat rejection to the subsurface?

The heat rejection is dependent on many different variables, like the flow velocity of the water through the system, the depth of the BHE, the diameter of the BHE, the groundwater level and the flow velocity of the groundwater. This results in that there is not a definitive answer to this question. The maximum obtainable heat rejection to the subsurface has to be investigated under specific fixed (known) parameters. In this phase of the research these parameters were not available and therefore assumptions have been used to construct the model.

In the Parametric Sweep section (10.1) BHE depth and volume of flow through the BHE have been varied. The largest depth resulted in the largest heat rejection.

With the variables that have been chosen for this model the heat rejection was more than sufficient for the target heat rejection. This amount could be increased by e.g. increasing the BHE depth. This would result in extra construction costs. An increase in heat rejection comes with an increase in costs, therefore, it is a trade-off that has to be considered before construction.

What impact does heat rejection to the subsurface have on the subsurface temperature?

The subsurface temperature increases due to the heat rejection from the BHE. After a period of lower or no heat rejection, the subsurface temperature (partly) restores to normal. Different conductivities are differently impacted by the heat rejection, the lower conductive (arid) top layer is less impacted, but retains the heat better. The higher conductive subsurface (saturated) layer is more susceptible to heating, but more able to conduct the heat away and therefore ‘recharges’ relatively quicker.

How does this impact the efficiency of the system?

The heat rejection of the BHE is negatively impacted by the increase of the subsurface temperature. This can be seen in the graphs in the result section. The energy that is rejected to the subsurface per second decreases as the subsurface temperature increases.

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14 APPENDIX

A. Reservoir Properties

Table 14-1: Reservoir properties

Reservoir properties					
Adopted from Bridge and Allen, 2013					
Facies	**0**	**1**	**2**	**3**	**4**
Description	**Floodplain deposits**	**Channel fill**	**Channel bed**	**Levee deposits**	**Point bars**
Lithology	Sandy **Silt** to silty **Sand**	**Gravel**, sandy	**Sand**, coarse grained and gravel	**Sand**, coarse grained, some gravel	**Sand**, medium grained
Reservoir properties					
Porosity (fraction)	0.42	0.32	0.32	0.32	0.38
Hydraulic properties					
Hyd. Conductivity (10*-4 m/s)	0.016	71	29	9.2	6
Specific Storage (10*-5 l/m)	30	2.9	2.2	2.2	9.6
Specific Yield	0.21	0.24	0.25	0.25	0.28
Thermal properties					
Heat Capacity (Solid) (x10*6 J/m3/K)	1.6	1.5	1.5	1.5	1.4
Ther. Conductivity (Solid) (J/m s K)	0.4	0.4	0.4	0.4	0.4
Heat Capacity (Aquifer) x10*6 J/m3/K)	2.69	2.35	2.35	2.35	2.38
Ther. Conductivity (Aquifer) (J/m s K)	2.54	2.74	2.74	2.74	2.67

B. Pictures

Figure 14-1: Well measurements on campus grounds

Figure 14-2: TRC building, targeted site for implementing Hybrid Cooling System