Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Workflow for Optimizing the Design of Close-Loop Deep Borehole Heat Exchangers

Martin PUJOL, Dimitri AYMARD

PO Box 201, Wembley, WA 6913, Australia

mpujol@rockwater.com.au

Keywords: close-loop, deep borehole heat exchanger, FEHM, direct-use, Australia, wellbore modelling, DBHE

ABSTRACT

Borehole heat exchangers have been used for heating and cooling of buildings and thermal storage for many years. The majority of systems are constructed of polyethylene pipe at depths that typically do not exceed 200 m. A fluid carrier (typically water) is continually circulated in the pipe allowing heat exchange between the bore and the surrounding rock mass in a geothermal closed loop. The borehole may also operate in heating only or cooling only modes. Then, the temperature is regenerated via heat transfer through conduction with the neighboring rocks in most of the geological contexts. If permeability exists, the heat can also be removed and the temperature conditions regenerated through advection/convection.

Some borehole heat exchangers have been constructed at greater depths; up to 3000 m worldwide. Deep borehole heat exchangers rely on circulating the fluid carrier down an open ended tubing inserted to the full depth of the borehole with heated water returning to surface via the annular space between the tubing and the bore casing though the reverse circulation mode is also possible. However, the number of deep borehole heat exchanger projects worldwide is limited and little applied research has been published on the ways to maximize the efficiency of deep borehole heat exchangers, for example the material selection for the tubing or the optimal geometry to meet the energy requirements cost-effectively.

Unlike conventional geothermal projects, borehole heat exchangers do not require high permeability values to be successful. This and other characteristics of the technology (such as scalability, retrofitting potential, etc.) have led to a renewed interest into deep borehole heat exchangers. In this study we present a workflow for optimizing the design of deep borehole heat exchangers and answering the basic question of long term operation using a real-world projects the authors are currently working on in Australia. The coupled thermo-hydro-mechanical simulator FEHM (Finite Element Heat and Mass transfer code) was used to model the deep borehole heat exchanger using appropriate python library tools.

1. INTRODUCTION

An overview of Deep Borehole Heat Exchangers (DBHE) around the world is provided by Sapinska-Sliwa et al (2015). Several real world examples that have been in operation for up to about 30 years were discussed in the paper.

Based on data in Sapinska-Sliwa et al (2015) and Deng et al (2020) the long-term direct heat transfer that have been achieved historically were calculated and are summarised below. The authors also report a maximum short term direct heat transfer of 370 kW for a system in Hawaii (USA) using a specially designed dual vacuum tubing.

DBHE	Depth (m)	Long-term direct heat transfer (kW)	Short-term max direct heat transfer (kW)	Power ratio (W/m)
Weissbad (Switzerland)	1213	38	-	**32**
Weggis (Switzerland)	2300	100	-	**44**
Aachen (Germany)	2500	120	-	**48**
Sucha Beskidzka (Poland)	4281	200	-	**49**
Prenzlau (Germany)	2786	150	-	**54**
Xi'an (China)	2500	273	-	**110**
Hawaii (USA)	1962	-	370	**188**

From the information above it appears that despite the range of geothermal gradients, depths, rock thermal conductivities and borehole heat exchanger constructions, the long-term direct heat transfer when expressed in W/m is moderately well constrained for the examples available between 32 W/m for the shallowest system (Weggis, Switzerland) and 110 W/m (Xi'an, China). Over short periods of time, the systems are capable of much greater direct heat transfer. The maximum short term direct heat transfer is only reported for Hawaii and, as can be expected, is much higher at 188 W/m particularly given the selection of specially design dual vacuum tubing with a very low heat conductivity.

Lous et al. (2015) estimated with the FEFLOW code, that a hypothetical 5 km DBHE would provide a long-term direct heat transfer of 150 kW to 600 kW (30 to 120 W/m) depending primarily on the tubing heat conductivity, flow rate and groundwater natural velocity.

We should also mention that Eavor Technologies Inc. has developed a novel approach to DBHE design called Eavor-Lite™. According to Eavor's website, the Derek Riddell Eavor-Lite™ Demonstration Project is a full-scale prototype of the Eavor technology suite. The project site is located near Rocky Mountain House, Alberta. Drilling and construction began in August of 2019. Eavor-Lite™ consists of two vertical wells, joined by two multilateral legs at 2400 m depth, connected by a pipeline at surface. Given that it includes some laterals, this novel design has the potential to increase the long-term direct heat transfer significantly when expressed in W/m, possibly towards the higher end and exceeding the range in Lous et al. and approaching maximum short term direct heat transfer reported above.

In this paper we use data from another real world project the authors have been involved with in Australia and the thermo-hydro-mechanical simulator FEHM (Finite Element Heat and Mass transfer code) to see how the design of a vertical DBHE may be optimized to maximize both the long-term direct heat transfer (base-load) but also the short term direct heat transfer (peak load).

In Chapter 2 we describe the geometry of a DBHE and the various design parameters that may be modified to optimize the thermodynamic efficiency of the systems. In Chapter 3 we present how the coupled thermo-hydro-mechanical simulator FEHM (Finite Element Heat and Mass transfer code) was used to model the DBHE using appropriate python library tools.

2. DEEP BOREHOLE HEAT EXCHANGER GEOMETRY

3.1 Description

As shown in Figure 1a, the DBHE consists of inner pipe (tubing) and outer pipe (annulus) connected at the bottom. During the operation, the fluid is pumped down through the inner pipe and comes back through the annulus extracting heat from ground. Thus, the mass flow rate and the borehole diameters (Figure 1b) influences the working fluid's velocity and its residence time down the annulus extracting heat.

Some key parameters to optimize the extraction have been highlighted by Doran et al. (2020). They include the use of insulated inner tubing which limits heat losses and/or conversely the use of an outer casing that has good thermal conductivity properties (or the absence of such casing such as in the Eavor-Lite™ concept) to ensure sufficient heat transfer occurs between the reservoir and wellbore. The optimization of a DBHE depends on adjusting the diameters dimensions that will affect the residence time of the working fluid, selecting efficient materials (eg Double layered tubing thermal conductivity 0.03 W/m/K and/or thermally enhanced grout), conducting sensitivity analysis for varying the mass flow rate and injection temperature to find the optimal extractible power.

Morita et al. (1985) have shown the necessity of insulating tubing to achieve reasonable output. Horne (1980) demonstrate that the reverse circulation configuration (down the annulus, up the tubing) results in larger thermal output. This is considered for the project studied in this paper in the sensitivity analyses (Chapter 3.3).

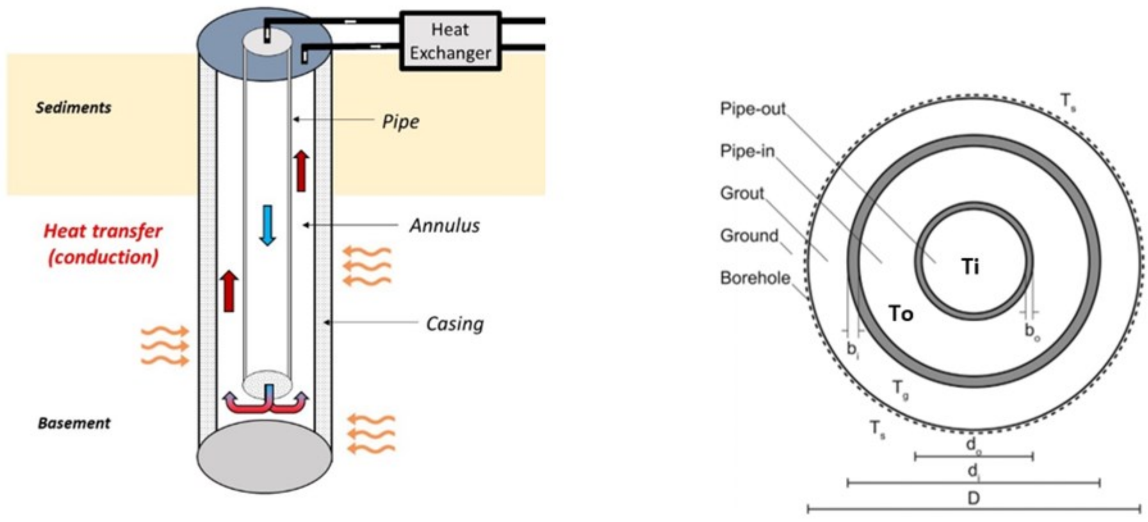

Figure 1: Deep Borehole Heat Exchanger geometry, vertical (a) and cross sections (b) – modified from Le Lous et al (2015)

3.2 Geology

In the real world project presented, the vertical DBHE intersects sediments overlying basement rocks (Figure 2). The rock properties for each formation within the sedimentary cover and the fresh basement are characterized and summarized in the Table below.

Unit	Rock density (kg/m^3)	Porosity (m^3/m^3)	Rock Specific Heat (kJ/kg/°C)	Bulk Thermal Conductivity (W/m/°C)
Brighton Group (sediments)	2700	0.20	0.68	1.45
Fyansford Fm (sediments)	2650	0.05	0.68	1.30
Werribee Fm (sediments)	2650	0.30	0.68	2.50
Basement rocks (cemented sandstone)	2650	0.05	0.92	3.70

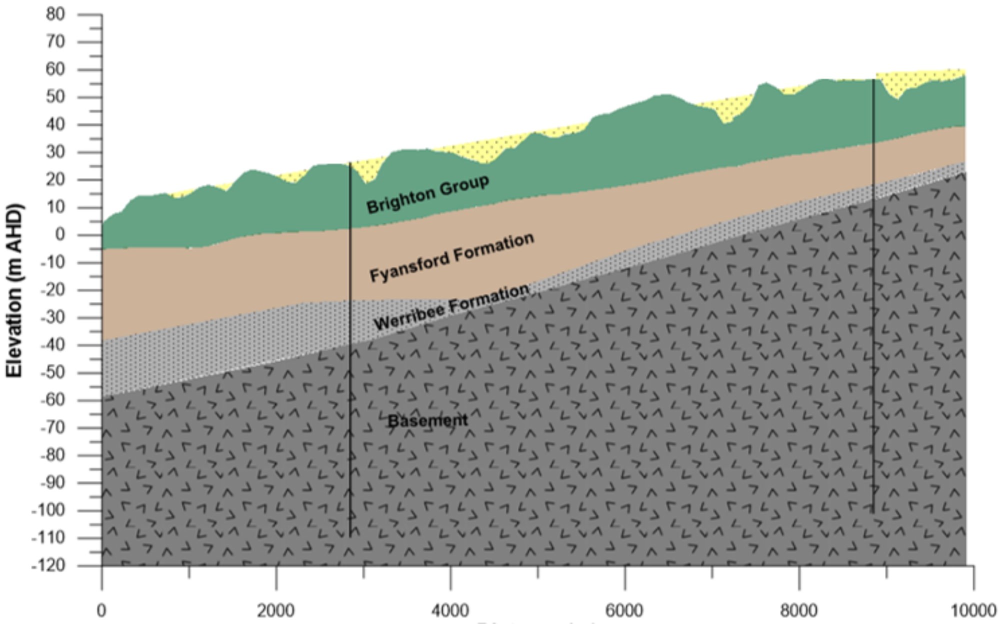

Figure 2: X-section through the project

3.2 Borehole design

The key components of a DBHE include:

- An optional cement-grouted surface pre-collar casing to isolate the sediments
- A casing to total depth (or open hole construction depending on rock permeability and stress field)
- An inner tubing used to circulate water down to the base of the borehole (internal) and back to surface (external) as shown on Figure 1a
- A surface heat exchanger and heat pump to allow extracting the maximum amount of energy out of the water and lowering of the injected water temperature to maximise the heat transfer

For optimal heat transfer the thermal resistance of the pre-collar casing and cement shall be maximized to minimize heat loss to the sediments. This can be achieved by using neat Portland cement mix and a uPVC casing with a low thermal conductivity.

The main casing however shall be selected to have a minimal thermal resistance to enhance heat transfer with the rock. This may be achieved by using thermally enhanced grout (for example with graphite flakes) and low carbon steel casing which has a high thermal conductivity.

Last but not least, the inner tubing shall have a very high thermal resistance (low thermal conductivity) to minimise thermal exchange between water inside and outside the pipe. This can be achieved by selecting a dual vacuum tubing or a Glass Reinforced Epoxy spoolable tubing (see example below in Figure 3).

Figure 3: Installation of spoolable tubing (photos provided by V Cardon – Orllati, 2020 for a project in Switzerland)

3. MODELLING WITH THE COUPLED THERMO-HYDRO-MECHANICAL SIMULATOR FEHM

3.1 Modelling methodology

The coupled thermo-hydro-mechanical simulator FEHM (Finite Element Heat and Mass transfer code) was used to model and design the DBHE, using appropriate Python library tools (model parameters outlined in Table below). The full length of the closed loop is considered embedded in and in contact with warm rocks, following the geothermal gradient (Figure 4).

Heat transfers from rocks to the fluid occur via conduction thought the cement, casing and tubing. The fluid flow into the bore is taken to be laminar. FEHM solves for Darcy heat and mass fluxes, mechanical stresses and displacements in a deformable porous media.

The two-dimensional axisymmetric computational domain is meshed using a radial grid extending 1 km away from the borehole heat exchanger. This grid, composed of 3,520 nodes and 50 layers, is refined for each bore component (that is, inner tubing, tubing thickness, annular space, etc.). Atmospheric pressure and temperature of 15°C are defined at the surface of this numerical model. No flow is defined at a radius of 1 km from the borehole.

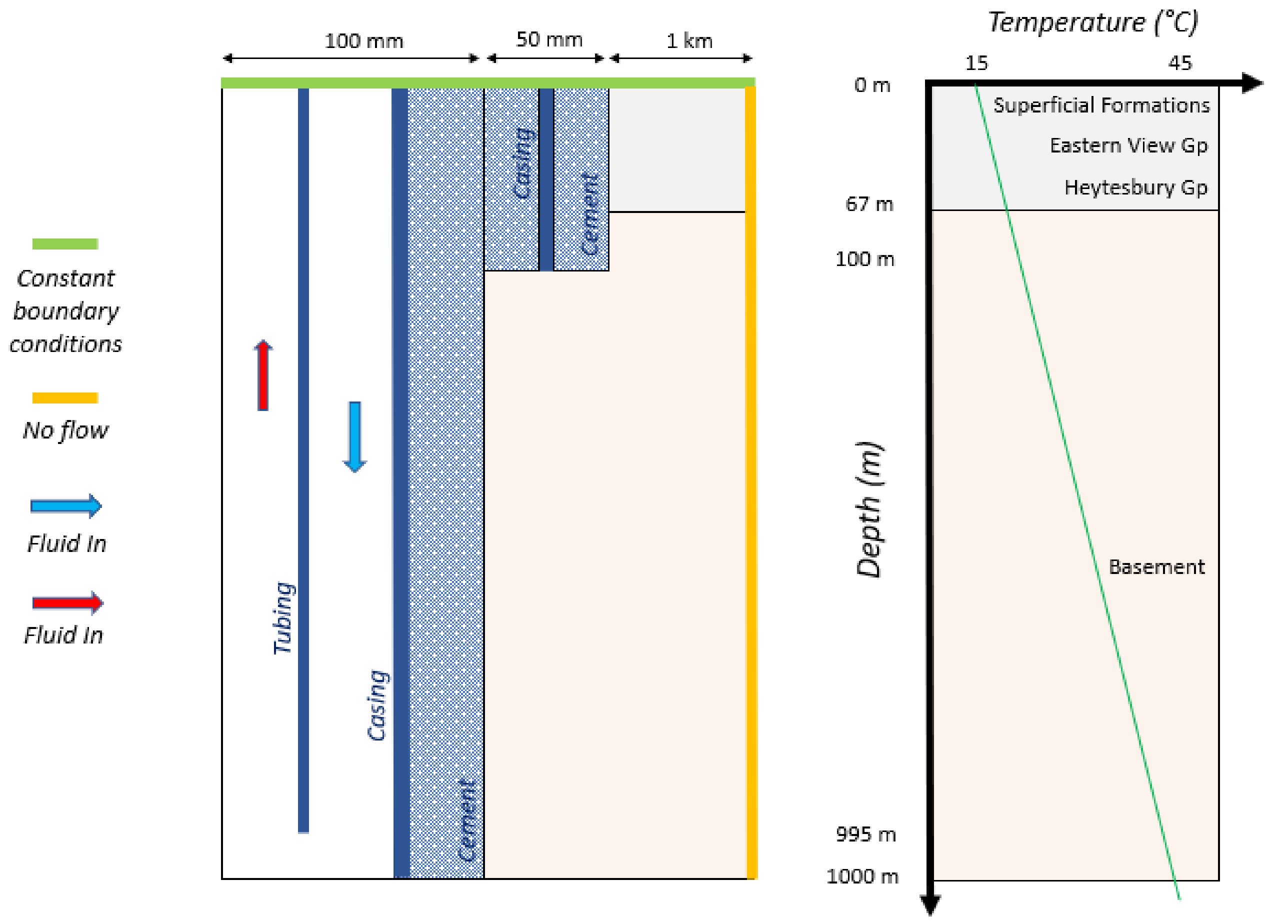

Figure 4: Cross-section and elements of a vertical borehole heat exchanger with annular outlet and centred inlet

Material	Density (kg/m^3)	Roughness (mm)	Specific Heat (kJ/kg/°C)	Thermal Conductivity (W/m/°C)
Spoolable GRE tubing	2050	0.005	1900	0.4
Surface casing (uPVC)	1450	0.005	1250	0.2
Portland cement (neat)	1600	-	750	0.5
Main casing (low carbon steel)	7850	0.500	510	54.0
Portland, silica mix	1600	-	750	1.5

3.2 Peak Heat Transfer

The model was first run for 15 time steps of 5 days each (75 days total) at increasing flowrates, ranging from 1 to 15 L/s, to estimate the peak heating capacity of a single DBHE. The injection temperature was assumed to be constant at 15°C, while the source temperature to the heat pump was calculated by the model.

Model-calculated DBHE outlet temperatures vary with the flowrate (that is, the lower the flow, the higher the temperature, as the fluid has more time to exchange heat with the borehole heat exchanger). The resulting temperature differential across the heat pump range from 3.6°C at 15L/s and 8.5°C at 1 L/s. These temperature differential values are adequate for geothermal heat pumps that can typically operate in the range 4–8°C.

The calculated peak direct heat transfer is 230 kW (about 230 W/m) for a relatively high flowrate of 15 L/s (Figure 3). This peak Power ratio compares well to the Hawaii example discussed in introduction given the shallower depth of the system studied. Such a high flowrate is calculated to require a 31 kWe circulation pump while the thermosiphon effect is calculated to allow a maximum flowrate of 1-2 L/s (ie at that lower flowrate the density difference between the inlet and outlet temperature is sufficient to drive the flow without using a circulation pump).

This indicated that a minimum of two deep borehole heat exchangers would be required to meet the real world peak winter load of 350 kW and that the operation in thermosiphon mode was not sufficient to meet peak loads (this would have required between five and nine boreholes).

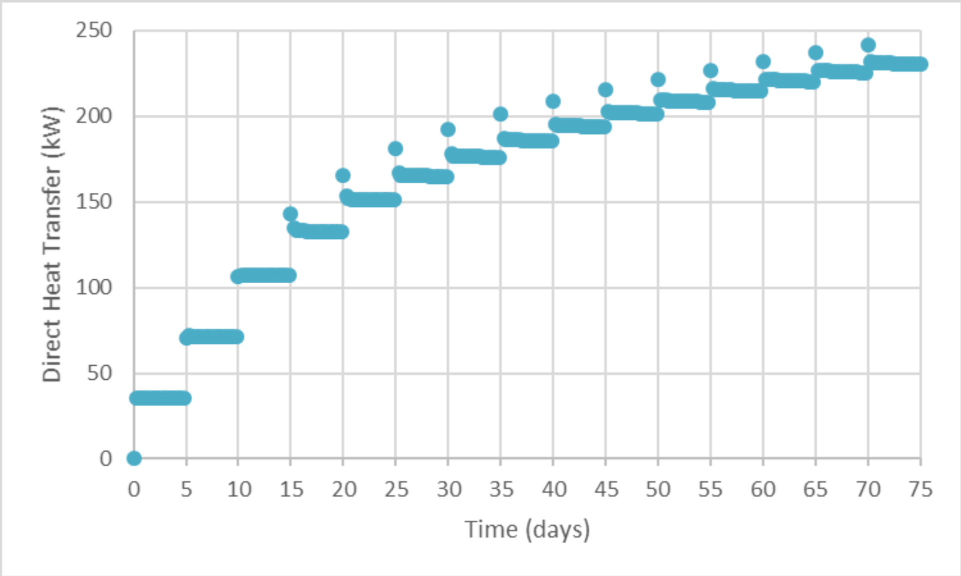

Figure 5: Peak Heat Transfer model results

3.2 Long-term direct heat transfer

Over time, the ground would cool down and the DBHE efficiency would start to decline. To simulate the potential decline in net COP over time, the model was run at the average annual heating load of the project (120 kW), split between two DBHE for 30 years of continuous operation. To maintain the required heat exchange over 30 years, the average flowrate through the borehole heat exchanger is predicted to be 1.5 L/s to 2.5 L/s (Figure 6), with only 10% of drop in the system coefficient of Performance over 30 years.

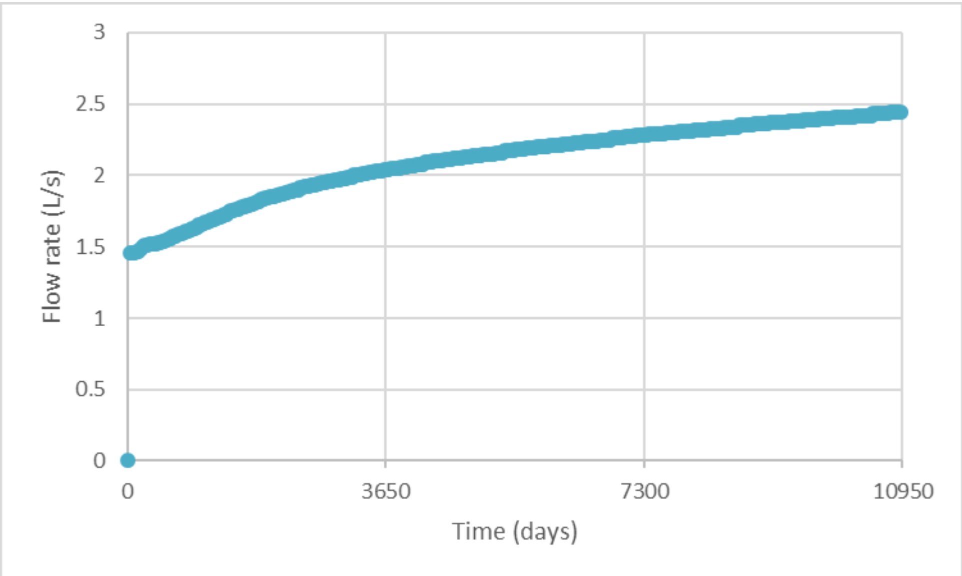

Figure 6: Long-Term Heat Transfer model results

This indicates that the optimised borehole heat exchanger has a long-term direct heat transfer of 60 kW (60 W/m). This is in the upper-end range of the Power Ratio discussed in the introduction given the use of thermally enhanced grout and low thermal conductivity tubing, and that of a circulation pump (ie the system is not operating in thermosiphon mode only unlike some of the example discussed in Introduction). As a rough order of magnitude the long-term heat transfer appears to be 4-5 times less than the peak transfer.

The FEHM model calculated temperatures radially from the borehole (below) suggest the two borehole heat exchangers need to be located at least 80 m from each other for minimal thermal interference.

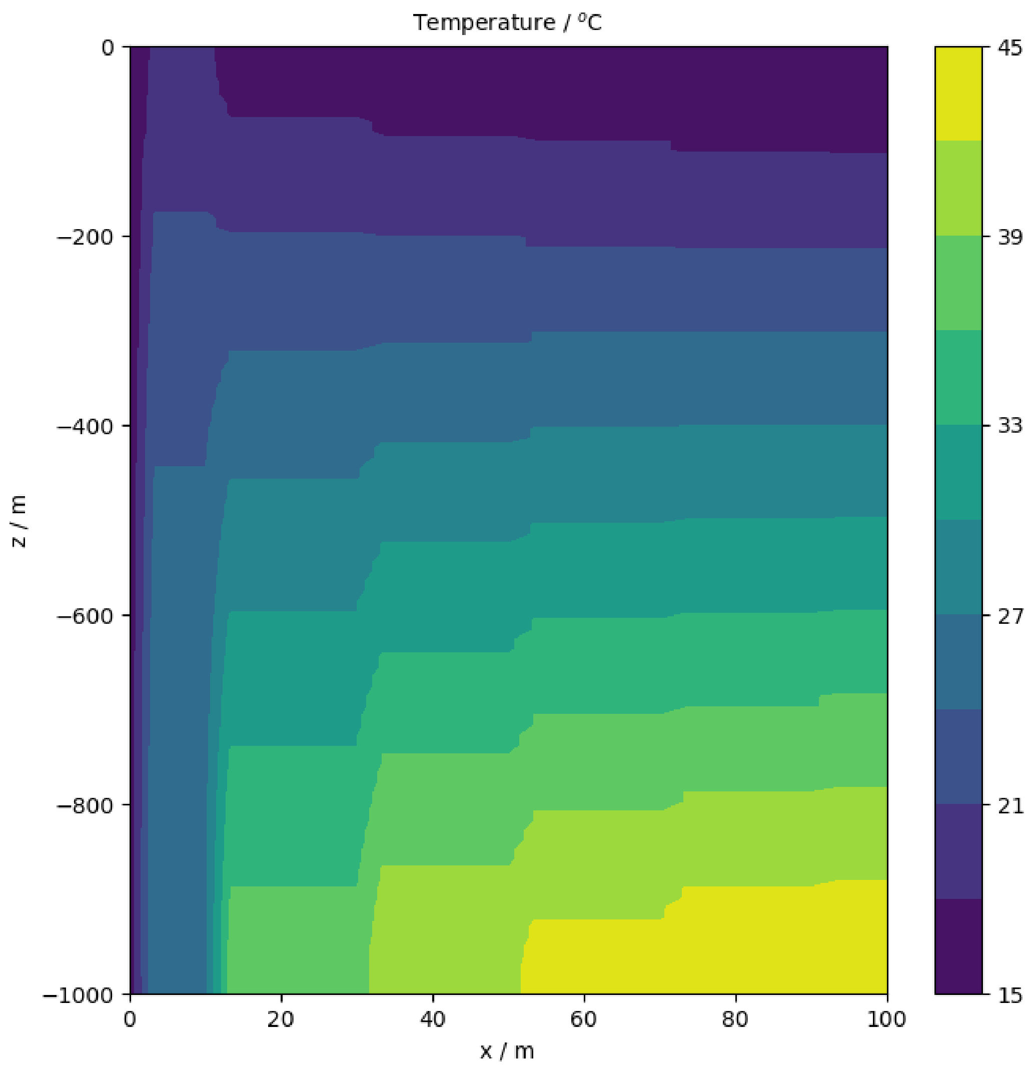

Figure 7: Modelled temperatures away from the DBHE after 30 years

3.3 Sensitivity

The model was re-run for 75 days at a constant flow rate of 5 L/s to assess the sensitivity of the thermal exchange to the following key parameters:

- Open-hole completion versus casing completion
- Thermal conductivity of inner tubing
- Thermal conductivity of grout
- Surface casing versus no surface casing
- Higher injection temperature (possibly not requiring a heat pump depending on the application)
- Larger diameter borehole

Overall the sensitivity analyses confirm that the borehole design is well optimised particularly when used in conjunction with a geothermal heat pump. However, open hole configuration is shown to be beneficial and shall be employed where the geological conditions permit it. Also, reverse circulation configuration (down the annulus, up the tubing) results in a larger thermal output for the borehole configuration considered (see Figure 8) as demonstrated by Horne (1980) previously.

Sensitivity Scenario	Thermal exchange @ 75 days (W/m)	Change (%)	Comments
Base case scenario	143.4	N/A	Base case scenario presented above
Open hole completion	146.9	+2.5%	Where rock strength and stress field allow open hole configuration is preferable
Steel inner tubing	142.5	-1.0%	The lower the thermal conductivity of the inner tubing the higher the thermal exchange
Non-thermally enhanced grout	112.7	-21.5%	Thermally enhanced grout (thermal conductivity of 1.5 W/m/°C) is having a strong impact on the short term thermal heat exchange capacity when compared to a grout with a poor thermal conductivity (0.5 W/m/°C) NB: the thermal conductivity of grout can be up to 5 W/m/°C for grout with graphite flakes (not modelled here)
No surface casing	138.2	-3.5%	The surface casing minimise heat loss to the shallower and colder surface sediments. While it increases the overall cost of the project it is worth considering since it appears to be more effective than the insulation of the inner tubing.
Injection temperature of 20°C	88.8	-38.0%	In the base case scenario a geothermal heat pump is used to maintain a constant injection temperature of 15°C. evidently the use of a higher injection temperature leads to less conductive heat transfer with the ground.
10" borehole	137.3	-4.3%	In the base case scenario the borehole diameter is 8". Somewhat counter-intuitively the heat transfer is less for a 10" borehole because of the thicker casing and cement grout for this dimension.
Reverse circulation configuration	150.0	+4.6%	Reverse circulation configuration (down the annulus, up the tubing) results in a larger thermal output for the borehole configuration considered (Figure 8) as demonstrated by Horne (1980) previously.

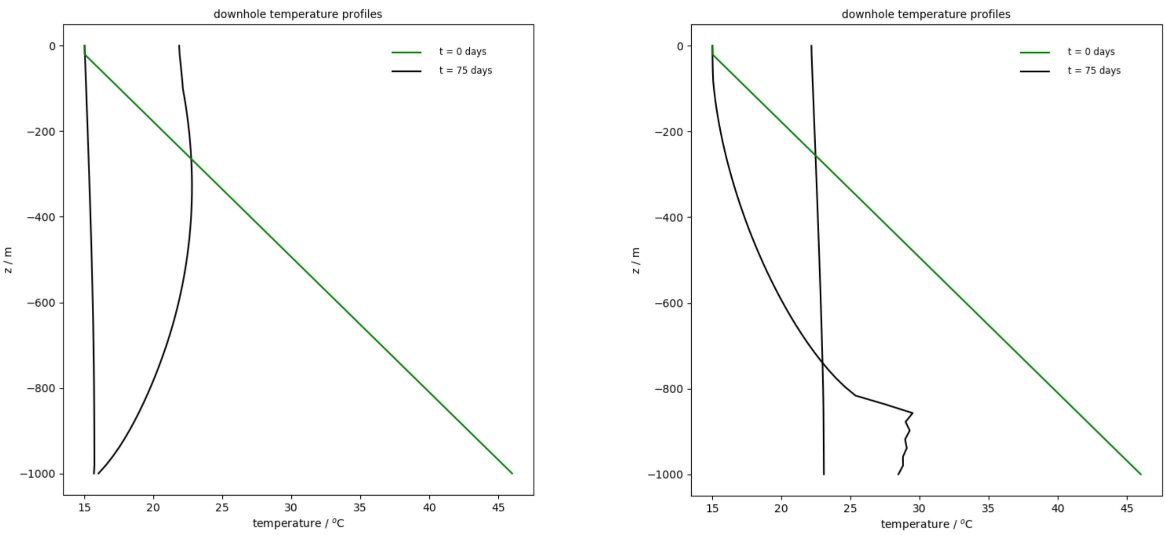

Figure 8: Base case circulation configuration (a) and reverse circulation (down the annulus, up the tubing) (b) configurations

4. CONCLUSION

While DBHE have a lower heat extraction and efficiency compared to conventional open systems, they can be a good alternative where conventional open systems are not viable because of insufficient permeability.

This paper summarises the workflow developed to design deep borehole heat exchangers and to maximise both the long-term direct heat transfer (base-load) but also the short term direct heat transfer (peak load) using a real-world project in Australia. The coupled thermo-hydro-mechanical simulator FEHM (Finite Element Heat and Mass transfer code) was used to model the DBHE using appropriate python library tools.

The worklow discussed in this paper highlights the potential to optimise the design of DBHE by using insulated tubing, thermally enhanced grout, surface casing to isolate surface sediments and where practical an open hole completion. Using the optimisations listed above it appears feasible to obtain short term heat transfer rates of 150 to 250 W/m with the use of a circulation pump. Le long-term heat transfer rate is typically 4-5 times lower, calculated at about 60 W/m for the real world example modelled.

The preliminary sensitivity work highlights which parameters the heat transfer is most sensitive too and can be used to evaluate the benefit of various DBHE design candidates.

Further work is needed to fully quantify the potential of the DBHE concept for large scale applications. Using field data will be helpful to validate this numerical wellbore-reservoir modelling tool and quantify the uncertainties in the pressure losses from the return fluid at the wellbore bottom. In addition, a variety of working fluids should be explored. Hybrid concepts where some groundwater flow may be possible to enhance the thermal exchange of the borehole should also be considered.

REFERENCES

Le Lous et al.: Thermal performance of a deep borehole heat exchanger: Insights from a synthetic coupled heat and flow model, *Geothermics 57 (2015) 157–172*

Deng et al.: Simulation Analysis on the Heat Performance of Deep Borehole Heat Exchangers in Medium-Depth Geothermal Heat Pump Systems, *Energies, MDPI, (2020) vol. 13(3), pages 1-28*

Doran et al.: Modelling an unconventional closed-loop deep borehole heat exchanger (DBHE): Sensitivity Analysis on the Newberry Volcanic Setting, *ResearchSquare (2020)*

Horne, R.N.: “Design Considerations of a Downhole Coaxial Geothermal Heat Exchanger,” Geothermal Resources Council Transactions, 4, 569, 1980.

Morita, K., Matsubayashi, O. and Kusunoki, K. (1985). Down-hole Coaxial Heat Exchanger Using Insulated Inner Pipe for Maximum Heat Extraction, GRC Transactions, Vol. 9, Part I, pp. 45-49.