Technical assessment of large scale groundwater cooling systems for low temperature geothermal power plants

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ABSTRACT

Within the framework of the Horizon2020 MATChING project, which aims to reduce the cooling water demand in the energy sector, innovative solutions are investigated to reduce water consumption and increase overall efficiency of low temperature geothermal power plants. In this respect, the feasibility of using direct groundwater cooling (GWC) as an alternative for wet cooling towers was evaluated. To study the effects of pumping large volumes of warm water on the pressure and temperature distribution in the groundwater, three dimensional dynamic heat- and flow models were developed and numerically solved. In addition, the sensitivity of the models was assessed by studying the impact of a number of key-properties on the model outcomes. The results of the project provided new insights into the main factors governing the technical feasibility of the groundwater cooling concept, and led to the overall conclusion that groundwater cooling provides a promising alternative for other cooling techniques, provided that a sufficiently thick and permeable aquifer is present, and that a large concession area is available to hold the numerous doublets that are required for these systems.

1. INTRODUCTION

Wet cooling towers (WCT) are one of the technologies that are traditionally used as heat sinks of low-temperature geothermal power plants (Walraven D. 2015). However, as thermal efficiency of these conversion units is limited to about 10%, the water consumption to cool down the plants is high. This stresses local water resources and hence comes with both an environmental and economic cost (Di Pippo R. 2012).

Hybrid cooling systems, and more specifically direct groundwater cooling may provide a novel strategy to tackle this problem (Ashwood A. and Bharathan D. 2011; Collins R. 2009; Russel H. and Gurgenci H. 2014). The technique encompasses the extraction of shallow aquifer water, which is subsequently used to provide additional cooling to power plants during the hot season. After each cooling cycle, the water is reinjected back into the aquifer at warmer temperatures. The distance between the extraction and injection wells needs to be sufficiently large to prevent an early breakthrough of the warm water front in the extraction wells. In addition, as the cooling demand of low temperature geothermal power plants is high, very large volumes of water need to be extracted from the aquifer, requiring a system with tens of doublets.

2. METHODOLOGY

The Belgian Balmatt geothermal power plant was used as a reference case for testing the feasibility of the concept and designing the well field to be used for cooling an Organic Rankine cycle (ORC). At Balmatt, the water is produced at a temperature of 128°C at depths of ca. 3300 m bgl and the full-scale potential of the project is 38 MW of heat production (Bos S. and Laenen B. 2017). The local geological characteristics have been used to parametrize the model; The local aquifer (the Cenozoïc 'Diest Formation') has a thickness of ca. 115 m, a permeability of 10 m/day, a natural hydraulic gradient of 0.001 m/m and a mean aquifer temperature of 11 °C.

Table 1: Thickness and hydraulic properties of the geological formations at the reference site (Balmatt plant, Mol, Belgium)

Layer type	Thickness (m)	K (m/day)	Porosity
top aquifer (Mol + Kasterlee fm)	25	9	0.3
Aquitard (Kasterlee clay)	10	0	0
cooling aquifer (Diest fm)	115	10	0.3
Aquitard (Boom fm)	50	0	0

Analytical considerations

When assuming a pumping flow rate of ca. 150 m³/h, analytical formulas indicate that distances between the extraction and the injection well of a doublet need to be in the order of several hundreds of meters to avoid thermal breakthrough within 30 years of operation (Banks D. 2009). The number of doublets required can be calculated based on the cooling capacity C which is given in equation [1]. C is the cooling capacity (kW), Q the flow rate (kg/s), T_{inj} the injection temperature (°C), T_{aq} the natural aquifer temperature (°C) and c_{water} the specific heat capacity of water (kJ/kg K).

$$C = Q.(T_{inj} - T_{aq}).c_{water} \qquad [1]$$

Given a conversion efficiency of the geothermal power plant of 10%, an aquifer temperature of 11°C and an injection temperature of 25°C, it can be calculated that 14 doublets are required to provide for the required cooling capacity of an 38 MW geothermal power plant.

Given the local geological conditions and an injection.

Numerical model

Because analytical formulas are not defined to study the interaction between tens of doublets, a numerical approach was followed. Dynamic 3D-heat and groundwater flow models were created using the TOUGH2 numerical simulation program (Pruess K. 1991). The simulations aimed to evaluate the effect of pumping large volumes of shallow groundwater on the temperature and pressure conditions in the cooling aquifer.

The conceptual model was populated with 4 geological layers. The cell size in the model varies between 50 x 50 and 350 x 350 m, resulting in ca 115 000 cells (Figure 1). The dynamic models were run for a time span of 30 years, corresponding to the estimated lifetime of the geothermal power plant.

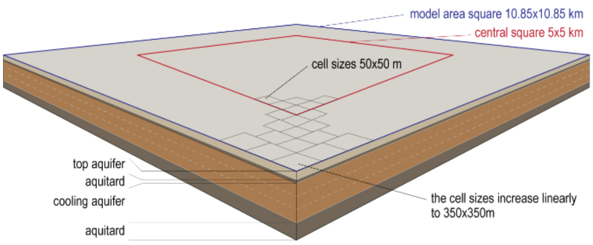

Figure 1: Design of the conceptual model used as input for the 3D numerical model build-up.

The groundwater cooling system on which this paper focused is displayed in Figure 2. During the summer season, water is extracted from the aquifer at ~11 °C and reinjected at 25 °C. Hence, the aquifer is heated up around the injection well. During the winter season, it is assumed that the heat produced by the geothermal power plant is directly used in a district heating network, and hence no cooling is required. During these months, water is extracted from the aquifer at 11 °C and cooled to 6 °C using air coolers before being reinjected into the aquifer. Introducing this extra cooling step reduces the temperature anomaly in the aquifer and hence extents the lifetime of the system.

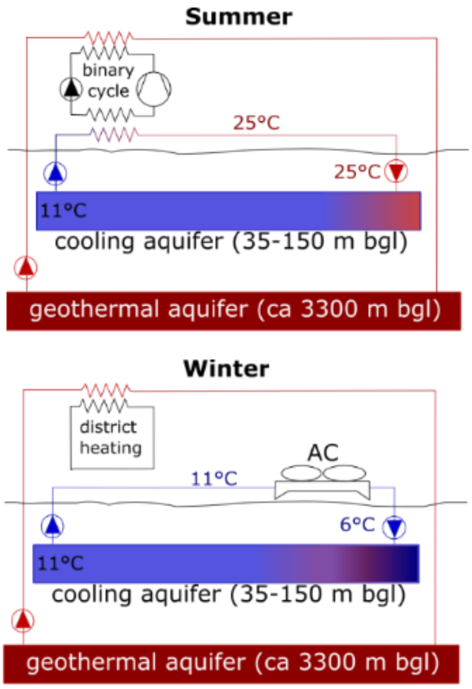

Figure 2: Seasonal groundwater cooling system: year-round extraction of cold groundwater with reinjection of warm water during the summer season and reinjection of cold water during winter.

3. AUTOMATED SENSITIVITY ANALYSIS

The technical feasibility of large-scale groundwater cooling installations depends on several interdependent geological factors (temperature, pressure, aquifer thickness, permeability, natural flow conditions, etc.) and design choices (flow rate, injection temperatures, well configuration, etc.). The uncertainty inherent to these parameters remaining the main risk factor, their impacts on the technical feasibility of the proposed concept was assessed. The sensitivity of the system was evaluated by studying the impact of a number of key-properties at discrete intervals, resulting in several hundreds of scenarios (Table 2).

Table 2: Values of the parameters used for the sensitivity analysis. The parameters of the reference model are underlined.

Permea-bility K (m/day)	Hydraulic gradient i (m/m)	Aquifer thickness H (m)	flow rate Q (m^3/h)
5	0	89	50
<u>10</u>	<u>0.001</u>	<u>114</u>	100
15	0.002	129	<u>150</u>
			200

To solve all these models, an automated workflow using PYTOUGH scripts was developed (Wellmann et al. 2012; Croucher A. 2014). This allowed for the model results to be compared in terms of temperature distribution, breakthrough time, required pumping power, and energy efficiency.

4. RESULTS AND DISCUSSION

4.1 Pressure- and temperature distribution

Results are discussed for a doublet configuration as shown in Figure 3. Nine doublets are organised at well distances of 500 m in a rectangular well field. A natural flow of 0.001 m/m is present in the aquifer, and pumping occurs at a constant rate of 150 m^3/h. During summer, water is injected at 25 °C; During winter, injection occurs at 6° C.

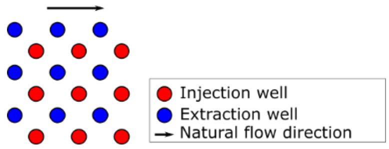

Figure 3: Well field configuration.

Figure 4 displays the temperature and pressure distribution in the aquifer after 30 years of seasonal groundwater cooling. One of the main challenges of designing a groundwater cooling system is too prevent early break-through of the thermal front around the injection wells into the extraction wells. Such a breakthrough would result in higher temperatures of the extraction water, thus reducing the cooling potential of the system. Figure 4 shows that after 30 years of operation, the thermal plumes have just reached the extraction wells, resulting in an average temperature increase of 0.4 °C.

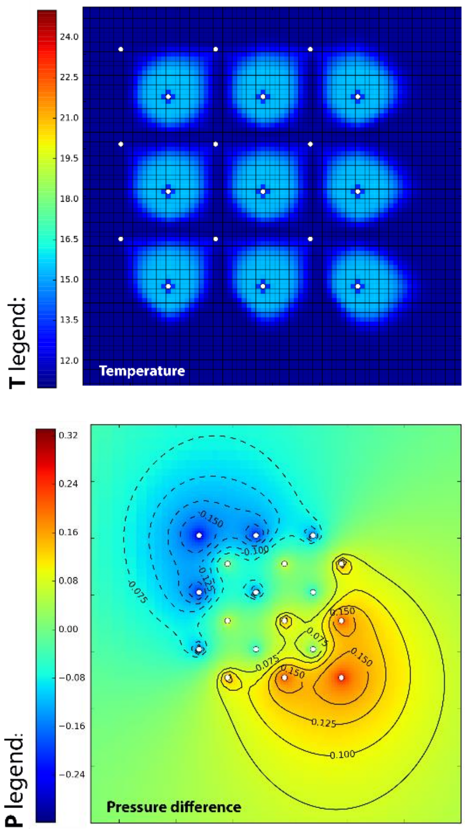

Figure 4: Temperature (left) and pressure distribution (right) in the aquifer after 30 years of operation.

Placing the wells further apart would increase the breakthrough-time, but would also entail a higher cost (requirement of larger well field areas and more piping). The temperature distribution around the extraction wells is not symmetrical due to the presence of an west-east directed natural flow. Another important parameter when designing GWC systems is the pressure build-up, or draw-down in the well field. Too large pressure differences would require very high pumping powers, hence increasing the cost of the system. Also, the static water level head of the aquifer might change over large areas, causing problems for other applications. However the model predicts rather limited pressure changes, of 0.3 bar maximum. This value is low thanks to the thickness of the aquifer (115 m) and its high permeability (10 m/day).

4.2 Model sensitivity

Using the reference parameters in figure 4, no problems regarding early breakthrough or pressure changes are to be expected. However, the geological and operational input parameters are all estimates, and it is not unlikely that when installing this system in the field, at least some of the parameters will prove to be different from the ones used in the reference model. Therefore the effect of changing a number of key model properties on the model outcome were analyzed.

The impact of varying input parameters on the efficiency of the system was investigated by analyzing two parameters, the pumping power required for each individual doublet and the cooling capacity of the entire doublet system. The first one, the pumping power required for each doublet, is defined by equation [1], with P the pumping power (kW), Q the pumping flow rate (m^3/h), H the total head that the pumps need to overcome (m), g the gravitational constant (9.81 m/s^2) and ρ the density of the fluid (kg/m^3). ŋ is the efficiency of the pump, which was set here at 70%.

$$P = \frac{Q \cdot H \cdot g \cdot \rho}{\eta \cdot 3.6 \cdot 10^6} \qquad [2]$$

The second system parameter analyzed is the cooling capacity of the entire doublet system. Its definition corresponds with equation [1], but is now calculated considering the entire lifetime of the system.

Combining these two variables gives a performance indicator regarding the degree of the energetic effectiveness of GWC in the setup under investigation (equation [3]).

$$Energy\ efficiency = \frac{C}{P} \qquad [3]$$

This parameter hence provides insights into the amount of cooling energy that can be delivered by the system, in comparison with the amount of energy that is required for the pumps the ensure the imposed pumping flow rate. Figure 5 summarises the variation of this parameter under the different input parameters (Table 2) evaluated in this study after the system has been in operation for 30 years. The figure shows that the energy efficiency decreases strongly with increasing flow rate because the required pumping energy increases significantly in those cases, in particular for scenarios with low hydraulic conductivities. The effect of the aquifer thickness is more limited, as is the impact of increasing the natural flow. Although decreasing the aquifer thickness and increasing the natural flow results in earlier break-through of the thermal front, this has only a limited effect on the overall cooling capacity when the entire lifetime of the system is considered.

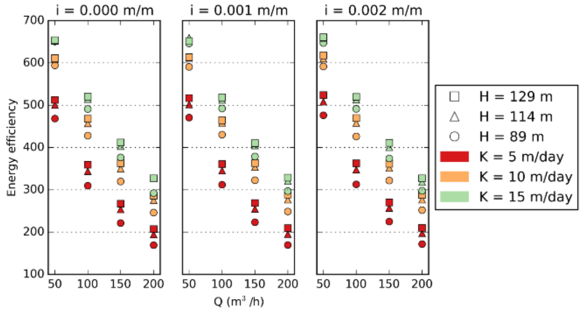

Figure 5: Energy efficiency of the cooling system versus pumping flow rate (Q), permeability (K), aquifer thickness (H) and natural flow direction (i).

Overall, this figure also demonstrates that the energy efficiency of these cooling systems is very high for each of the modelled scenarios, clearly demonstrating the potential of the systems under study as cooling sources. Best-case scenarios are those where a low pumping flow rate is imposed, where the hydraulic conductivity is high and the aquifer is the thickest.

However, it has to be kept in mind that the scenarios with the highest energy efficiency do not automatically correspond with the most optimal cases overall, because pumping at a lower flow rate requires a larger number of doublets, which encompasses a higher costs for installation, maintenance and piping in addition to a significantly larger concession area.

Figure 6 illustrates this aspect. The aquifer area in which temperature increases are over 0.5°C is always large, with areas over 10 km² when pumping at 150 m³/h and cooling down a full-scale geothermal plant operating at a conversion efficiency of 10%. The figure shows clearly that reducing the pumping flow rate to increase the energetic performance of the system comes with a high cost: reducing the pumping flow rate to 50 m³/h more than doubles the number of doublets required and triples the area in which the aquifer is affected.

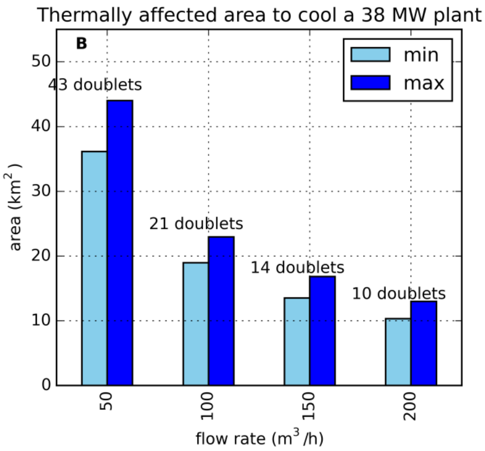

Figure 6: Minimal and maximal thermally affected area under the different input parameter choices (Table 1) when considering the total amount of doublets that are required to cool down a full-scale plant. The thermally affected area is defined as the area in which the aquifer temperature is higher than the natural temperature +0.5 °C. Areas are calculated based on rectangular bounding boxes.

An important result of the sensitivity analysis is the limited effect of the input parameter variations on the overall cooling capacity of the system under a fixed pumping flow rate (Figure 7).

The initial cooling capacity of a system is defined by the difference between the injection temperature and the natural aquifer temperature. It remains constant up to the point of thermal breakthrough. Afterwards, it decreases linearly with increasing extraction temperature. The cooling capacity at the end of the production period can hence be smaller than the initial capacity.

To evaluate the overall thermal efficiency of a GWC-system it is important to consider the integrated cooling capacity over the entire production period. This is so because, for example, a scenario with a breakthrough after 10 years with maximal temperature increases in the extraction wells limited to 0.7°C may be able to provide more overall cooling when compared to a system with breakthrough after 25 years and extraction temperatures increasing with 1.5°C.

In figure 7 the initial, integrated and final cooling capacities are plotted against pumping flow rate. The cooling capacities were calculated for each flow rate considering only those parameter combinations (Table 2) that resulted in worst-case scenarios in terms of thermal break-through.

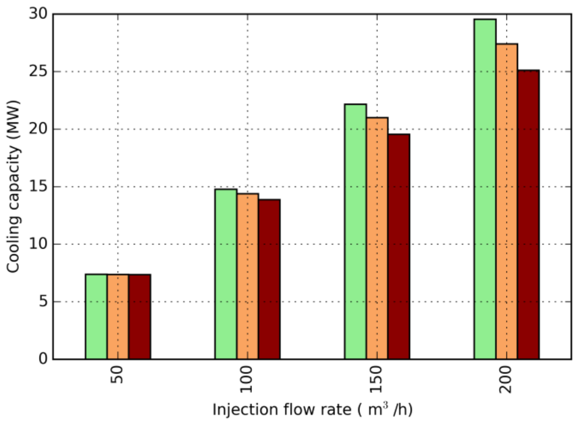

Figure 7: Comparison between initial cooling capacity (green), integrated cooling capacity (orange) and final cooling capacity after 30 years of production (red), considering only the worst-case scenarios for each pumping flow rate.

This figure shows that sensitivity of the average cooling capacity towards parameter changes is less pronounced than that of the final cooling capacity. For example, maximal decreases from the initial- to the average cooling capacity for the 150 m³/h case are ca. 1 MW, which is a difference of less than 10% when compared to their initial capacity.

This conclusion is important because traditionally, system designs aim to fully avoid thermal breakthrough within the production period. However, our results show that even for cases with significant breakthroughs (in worst-case scenarios breakthrough occurs earlier than 15 years and aquifer temperature increases withup to 3.5°C), the average cooling capacity of the GWC will remain at least at 90% of its initial value.

Similar conclusions were made by Sommer W. et al. (2015), who performed an optimization analysis for the well configurations of ATES-systems. Given the large concession area that is required to install the GWC systems under study here, it could hence be interesting to consider placing the wells at such distances that an average cooling capacity of e.g. 95% of its design value can be guaranteed instead of focussing on completely avoiding thermal breakthrough.

CONCLUSIONS

The potential of groundwater cooling (GWC) as a new cooling technique for low temperature geothermal power plants using ORC technology was assessed by developing 3D numerical heat and flow models. Sensitivity analyses proved invaluable in providing insights into the effects of varying geological and operational parameters on the efficiency of the systems. The results demonstrated that the energy efficiency of GWC is very high and that the technique hence provides a promising and technically feasible alternative for other cooling techniques, provided that a sufficiently thick and permeable aquifer is present, and that a large concession area is available to hold the numerous doublets that are required for these systems. To limit costs related to piping material and concession area, system designs should not focus on completely avoiding thermal breakthrough, as the results showed that the overall cooling capacity is influenced only to a limited extent by early break-throughs.

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