Simulation of closed-loop geothermal systems

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Summary

Results from the EU-Horizon project HOCLOOP to qualify and develop technology for deep geothermal energy from closed-loops are presented. The first step in the project has been to benchmark several software tools to simulate deep coaxial borehole heat exchangers. Then, the software has been applied to the design of geothermal systems that can deliver 1 MW of hot water for large buildings or district heating. The simulations show that when the geothermal gradient is 30 °C/km, at least a 3 km deep well with a 3 km horizontal segment is needed to produce the power when the heat conductivity is 2 W/m/K surrounding the vertical well and 3 W/m/K surrounding the horizontal segment. The simulations show a gentle decline in power production over tens of years (maybe much more than 100 years) after a short thermal transient. The injection temperature is 30 °C and the output temperature stays above 70 °C after 50 years, except for the shallowest test well.

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Introduction

Global warming is attributed to CO_2 emissions primarily from the burning of fossil fuels. The need for alternatives to fossil fuels has led to an increased interest in geothermal energy from closed systems. It is an emission-free energy source which occupies a small surface area. Shallow closed-loop geothermal energy has been successful in heating or cooling buildings in a range of sizes from private homes to hospitals and airports. The upscaling from shallow to deep closed-loop geothermal energy is still in the early stage of development. Among the reasons are the uncertainties related to the subsurface, the cost of drilling and the well design. Another reason is the lack of reliable future predictions of energy production.

There are at least two technologies for exploiting deep geothermal energy, an open and a closed system. The closed-loop technology has several advantages over an open solution. An open geothermal system has two wells, one injection well and one production well. The rock in between the two wells has a fracture network that serves as a heat exchanger. The fracture network is normally made by hydraulic fracturing, which includes the risk of triggering seismicity. Another challenge is that it is difficult to know in advance the suitability of the fracture network for use as a heat exchanger. Under geothermal heat production, the rocks in the fracture network will interact with the fluid. The oil industry has experienced that fluid-rock interaction often leads to mineral precipitation in fractures, wells and in surface installation.

Simulation results from the EU-Horizon project HOCLOOP (A circular by design environmentally friendly geothermal energy solution based on a HOrizontal Closed LOOP) are presented here. The aim of the HOCLOOP project is to qualify and develop technologies for closed-loop geothermal heat extraction from deep wells. The HOCLOOP project is based on a coaxial heat exchanger, where the “cold” fluid is heated from the surrounding rock on its way down the annulus. When the heated fluid reaches the bottom of the well, it returns to the surface through an inner tube that is insulated from the annulus.

Simulation software

The HOCLOOP project uses different software for the simulation of coaxial borehole heat exchangers. Among the simulators, the following three simulators were benchmarked and applied to this study:

GWellFM (Geothermal Well Flow Model, IFPEN) is a steady state, 1D non-isothermal axisymmetric, multi-component, and two-phase flow simulator (Leontidis et al., 2023). The simulator solves for 2D transient heat flow in the rock, and it assumes a stationary thermal state in the fluid. GWellFM is fully compositional concerning the fluid phase. The fluids are assumed to be in thermodynamic equilibrium in the well and several equations of state have been integrated for providing thermodynamic properties. GWellFM is coupled to the 3-D fracture flow simulator FraXim (also from IFPEN) for cases with heat convection by Darcy flow in the rock and for fluid flow in fractures.

GTW (Geo-Thermal-Well, IFE) is a single-phase and semi-transient geothermal simulator in cylinder coordinates (ref. in preparation). The simulator solves the temperature equation for conductive cooling in the rock. The cylinder symmetry restricts the simulator to deal with heat advection to cases where the fluid flow is parallel to the well. Energy conservation in the rock and the well is solved coupled, using an energy-conservative finite volume method. The continuity and the momentum equations for the well are solved for a stationary one-phase fluid using tabulated thermodynamic data.

COMSOL Multiphysics® (VITO) is a commercial software for various physics and engineering applications based on the finite element method. The software allows the user to design the numerical domain, to couple different physical processes, to solve the resulting partial differential equations and finally to post-process the results.

Software benchmarking

The software was benchmarked against each other and the analytical solutions of Ramey (Ramey, 1962) and Kabir (Al Saedi et al., 2018, Sharma et al. 2020) by running a series of benchmark cases (Leontidis et al, 2023). One test is a fully cased well (Fig. 1: Case h) with different casings at different depths. The total depth of the well is 1828.8 m, the casing internal diameter is 0.1617 m, and the casing outer diameter is 0.1778 m. The first casing goes to 1000 m and the second casing goes to the bottom of the well. The rock has a heat conductivity of 2.423 W/m/M, a heat capacity of 902.67 J/kg/K, and a density of 2600 kg/m3. The surface temperature is 21.1 and the temperature at the bottom of the well is 48.8. Fig. 2a and 2b show the annulus temperature after 1 year and 10 years, respectively, and Fig. 2c shows the output temperature for the three simulators together with Ramey's analytical solution. The simulation results are in good agreement with each other and with Ramey's solution. The Ramey solution is a good approximation in this case because the inner tube is insulated from the annulus, although its heat conductivity is 0.1 W/m/K.

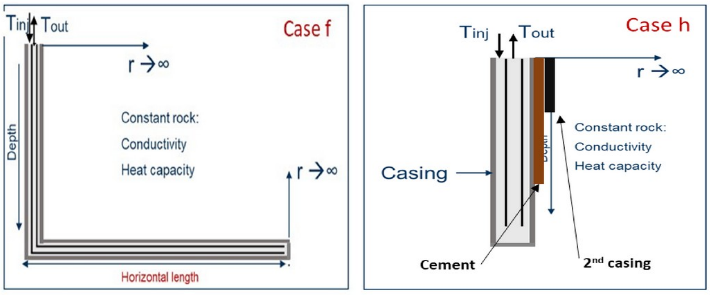

Figure 1 *The benchmark case of a fully cased well with different casings at different depths (case h) and a closed horizontal well (case f). (Q=fluid flow rate, Tinj=injection temperature, r=radius.)*

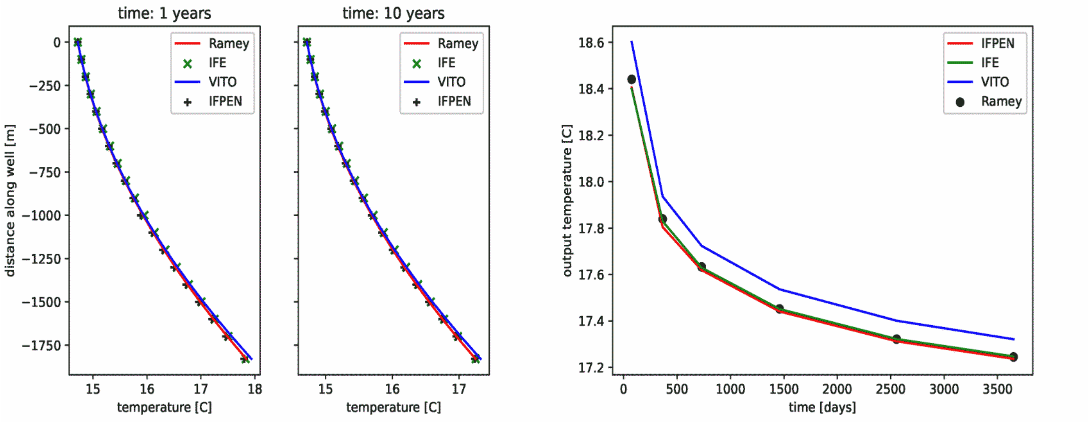

Figure 2 *The annulus temperature for the well in the benchmark study after (a) 1 year and (b) 10 years. (c) The output temperature as a function of time.*

Some of the benchmark cases revealed minor differences between the simulators. These differences could be explained by different discretizations of space and time, slightly different fluid properties, different Nusselt numbers for different Reynold numbers and different geometry dimensions (COMSOL was run with a full 3D domain).

Simulation results

Several versions of a closed horizontal geothermal well were simulated (Fig. 1: case f), where it goes down to 4 km and then into a horizontal segment of 5 km (reference configuration). The inner and outer diameters of the annulus are 122 mm and 140 mm, respectively. The corresponding diameters of the tubing are 85 mm and 101 mm, respectively, with a heat conductivity 0.01 W/m/K. The geothermal gradient is 30 °C/km, and the rock heat conductivity is 2 W/m/K for the vertical part and 3 W/m/K for the horizontal part. The injection temperature is 30 °C and the flow rate in the reference configuration is 7.5 kg/s. The implications of different flow rates, well depths and horizontal lengths were tested.

Figures 3a and 3b show the well temperature, Fig. 3c the output temperature of the fluid and Fig. 3d the power produced for different flow rates. By increasing the flow rate, the power produced from the system also increases (Fig. 3d) because the power is proportional to the flow rate, but at the same time, the output temperature decreases (Fig. 3c) because the time the fluid remains in contact with the hot rocks is less.

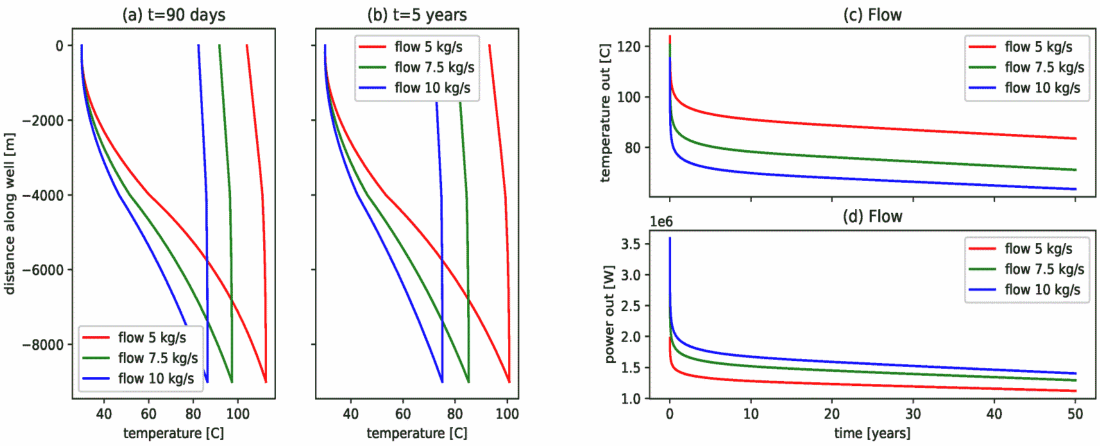

Figure 3 *The well temperature at 90 days (a) and at 5 years (b) for the three flow rates 5 kg/s, 7.5 kg/s and 10 kg/s. The output temperature (c) and the power (d) as a function of time.*

The depth of the well and the length of the horizontal segment have a strong impact on the output temperature and the power produced. Figures 4a, 4b and 4c indicate that the output temperature is increasing by 20 °C per extra km of depth, with an increase of almost 0.5 MW of power per extra km of depth. The plots of Fig. 5 show that going from 2 km to 5 km of horizontal segment gives a larger performance increase per km of horizontal well than going from 5 km to 7 km, indicating that there is an optimum length for which the fluid recovers the maximum available energy from the surroundings. Going beyond this length and considering the drilling cost, has no further added value.

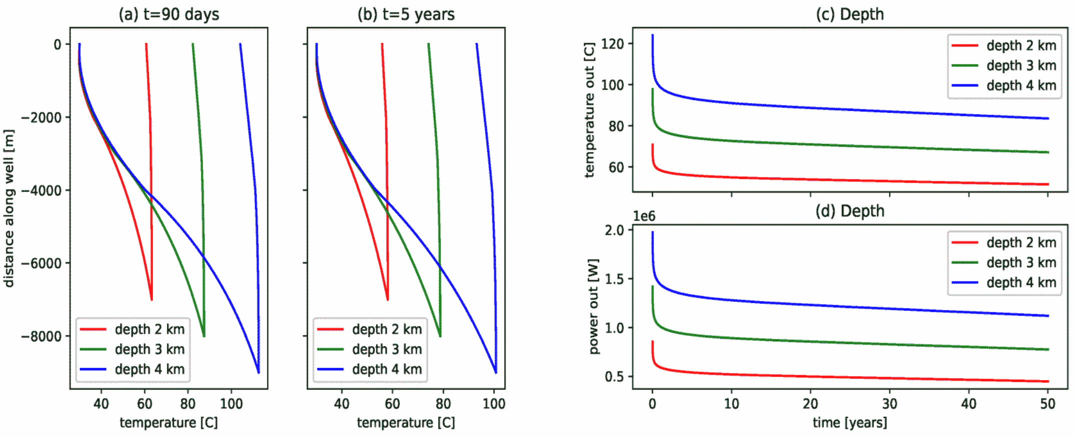

Figure 4 *The well temperature after 90 days (a) and 5 years (b) for three depths. The output temperature (c) and the power (d) as a function of time.*

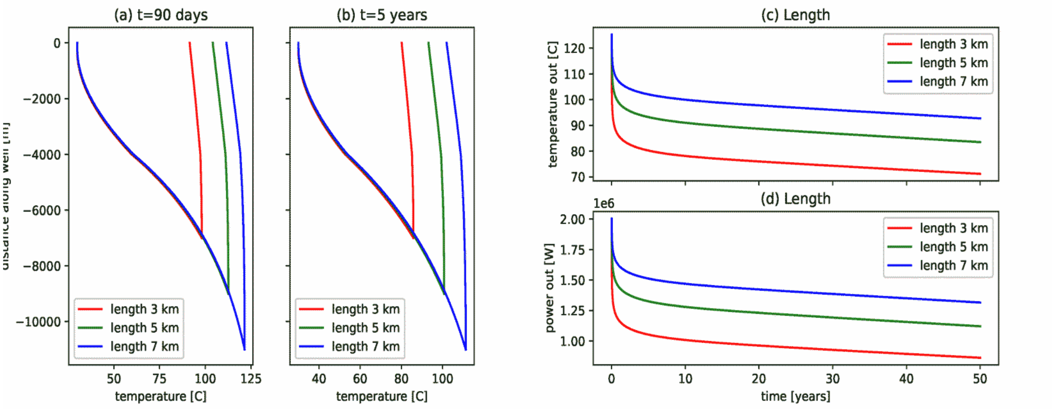

Figure 5 *The well temperature after 90 days (a) and 5 years (b) for the three horizontal lengths. The output temperature (c) and the power (d) as a function of time.*

Conclusions

Results from the EU-Horizon project HOCLOOP to qualify and develop technology for deep geothermal energy from closed-loops are presented. The first step in the project has been to benchmark several software tools to simulate deep coaxial borehole heat exchangers. Then, the software have been applied to the design of geothermal systems that can deliver 1 MW of hot water for large buildings or district heating. The simulations show that when the geothermal gradient is 30 °C/km, at least a 3 km deep well with a 3 km horizontal segment is needed to produce the power when the heat conductivity is 2 W/m/K surrounding the vertical well and 3 W/m/K surrounding the horizontal segment. The simulations show a gentle decline in power production over tens of years (maybe much more than 100 years) after a short thermal transient. The injection temperature is 30 °C and the output temperature stays above 70 °C after 50 years, except for the shallowest test well.

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References

Leontidis, V., Niknam, P., Durgut, I., Talluri, L., Manfrida, G., Fiaschi, D., Akin, S. and Gainville, M. [2023]. Tools for Modelling Reinjection of Two-Phase Non-Condensable Gases and Water in Geothermal Wells. *Applied Thermal Engineering*, **223**, 120018.

Ramey Jr., H. [1962]. Wellbore heat transmission. *Journal of Petroleum Technology*, **14**, 427-435.

Al Saedi, A., Flori, R. and Kabir, C. [2018]. New analytical solutions of wellbore fluid temperature profiles during drilling, circulating, and cementing operations. *Journal of Petroleum Science and Engineering*, **170**, 206-217.

Sharma, P., Al Saedi, A. and Kabir, C. [2020]. Geothermal energy extraction with wellbore heat exchanger: Analytical model and parameter evaluation to optimize heat recovery. *Renewable Energy*, **166**, 1-8.

Leontidis, V., Acevedo, E. H., Wangen, M. and Harcouët-Menou, M. [2023]. The HOCLOOP Project: Tools to model heat extraction from horizontal closed wells. *4th EAGE Global Energy Transition Conference & Exhibition*, Extended Abstracts.