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Design of a hybrid deep coaxial heat-exchangers with hydrothermal component using numerical simulations and analytical solutions

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ABSTRACT

This work presents the rehabilitation of the deep geothermal well Thônex-1 (Geneva, Switzerland) into a hybrid coaxial borehole heat exchanger that combines a closed-loop system with an artesian hydrothermal flow. Various modelling approaches (analytical, semi-analytical and 3D numerical) were used to estimate long-term thermal performance over 50 years and for optimization purpose. A newly developed analytical model, validated against FEFLOW simulations, showed that even a modest artesian flow rate (0.1 l/s) can increase heat output from 112 kW to 144 kW (+28%) while significantly improving thermal sustainability. This concept demonstrates strong potential for repurposing underperforming hydrothermal wells or depleted O&G boreholes and supporting the energy transition across Europe.

1. INTRODUCTION

As part of the "GEothermies" Program, the Services Industriels de Genève (SIG) decided to rehabilitate the deep geothermal borehole Thônex-1 to supply low-carbon heating to the growing urban district of Communaux d'Ambilly in the Municipality of Thônex in Canton Geneva. Originally drilled in 1993 for hydrothermal exploration, the well reached a total drilled length of 2700 m corresponding to a vertical depth of 2530 m, targeting the Malm reef complex.

Despite an estimated bottom-hole temperature of 88°C, production tests revealed insufficient artesian flow (0.3 l/s), attributed to low permeability due to cemented Jurassic limestones. For over a decade, the wellhead remained abandoned. Renewed geothermal interest in 2008 and the planned development of a low-energy district of Communaux d'Ambilly prompted SIG to rehabilitate the site. Given the risk of re-drilling an aged and deviated well, SIG opted for a conservative rehabilitation strategy, repurposing the borehole to be equipped with a deep coaxial borehole heat exchanger. From 2018 to 2021, multiple feasibility studies and simulations were conducted, including the development of a novel hybrid system that leverages natural artesian flow (18°C, 5–6 bar at the surface) to improve heat extraction via upward flow in the annular space around the coaxial borehole heat exchanger.

The present abstract described the methodology used starting 2018 to estimate the performance of the deep coaxial borehole heat exchangers, leveraging the natural artesian flow.

2. SITE CONDITIONS

The Thonex-1 deep well lies in the municipality of Thônex in the Canton of Geneva, Switzerland. Beneath a 73 m thick Quaternary glacial deposit lies a sandy and marly Swiss Molasse sandstone down to a depth of about 1250 m. Cretaceous limestones are encountered at a depth of 1331 m, followed by Malm and Oxfordien reef limestones (Fig. 1). Well tests carried out in 1996 indicate a hydraulic conductivity of between 10^{-4} m^2/s and 10^{-6} m^2/s. This transmissivity was considered too low for a sustainable and economic use of the well. The tests identified an artesian flow in the well, with a stabilized flow rate of about 0.3 l/s.

A bottom hole temperature of 88°C was extrapolated from an incomplete temperature log recorded down to 1900 m below the surface, indicating a geothermal gradient of approximately 3.12 K/100 m, which correspond to the average geothermal gradient observed in Switzerland. During the tests, the wellhead temperature stabilized at approximately 18°C after 10 days.Two thermal response tests were carried out in 2021 in two shallow BHE close to the Thônex-1 deep well. Thermal conductivity of about 2.15 $Wm^{-1}K^{-1}$ were measured. Laboratory measurements on the carbonate limestones at a depth of 1788 m give a value of 2.72 $Wm^{-1}K^{-1}$.

3. METHODOLOGY

3.1 Modelling approaches

Preliminary studies carried on in the 90's estimated a thermal output of about 100 kW using the well as a coaxial BHE to a depth 1800 m. Based on thermodynamic laws and simplified assumptions, an additional power of 100 to 150 kW was estimated when the hydrothermal artesian component is used as an additional heat source.

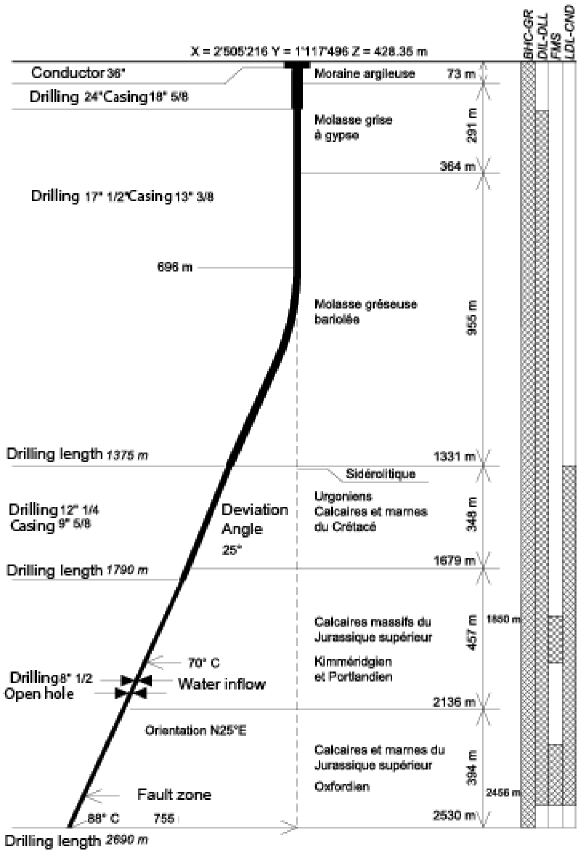

Figure 1: Design of the deep deviated well Thônex-1 together with the stratigraphy

To verify this assumption, a comprehensive modeling strategy was implemented using different approaches. In addition, a new analytical approach was developed.

The first approach involves tools commonly applied for the design of conventional vertical BHE, such as the software EWS (Huber 2020). These tools are based on a hybrid approach of analytical solutions (outside the borehole) coupled with numerical calculations (inside the borehole). Such hybrid tools allow for fast calculations (in the order of a few seconds for a 50-year simulation). However, they cannot simulate settings involving deep hydrothermal circulation.

The second approach relies on modelling software based on numerical methods, such as the FEFLOW software developed by DHI (Diersch 2005). This software is based on the finite element method and is primarily designed to simulate subsurface flow systems with or without mass and/or heat transport. However, it is also possible to simulate systems that consider only mass or heat transport processes, such as vertical BHE. FEFLOW offers three modelling options (Diersch 2014). The first option consists of a detailed and explicit 3D discretization of the borehole (Fig. 2, top). This 3D mesh includes all elements of the borehole, such as the tubing, the cement and the casing. This option allows for the simulation of complex systems but is computationally intensive. Simulating 50 years of operation may take several weeks. As such, this option is not well suited for optimization calculations. In the second option the BHEs are represented as embedded 1D elements that are linked to the 3D mesh. Heat transfer within the heat exchanger is calculated using an embedded finite-element model, applying either a numerical or simplified analytical approach (Fig. 2, middle).

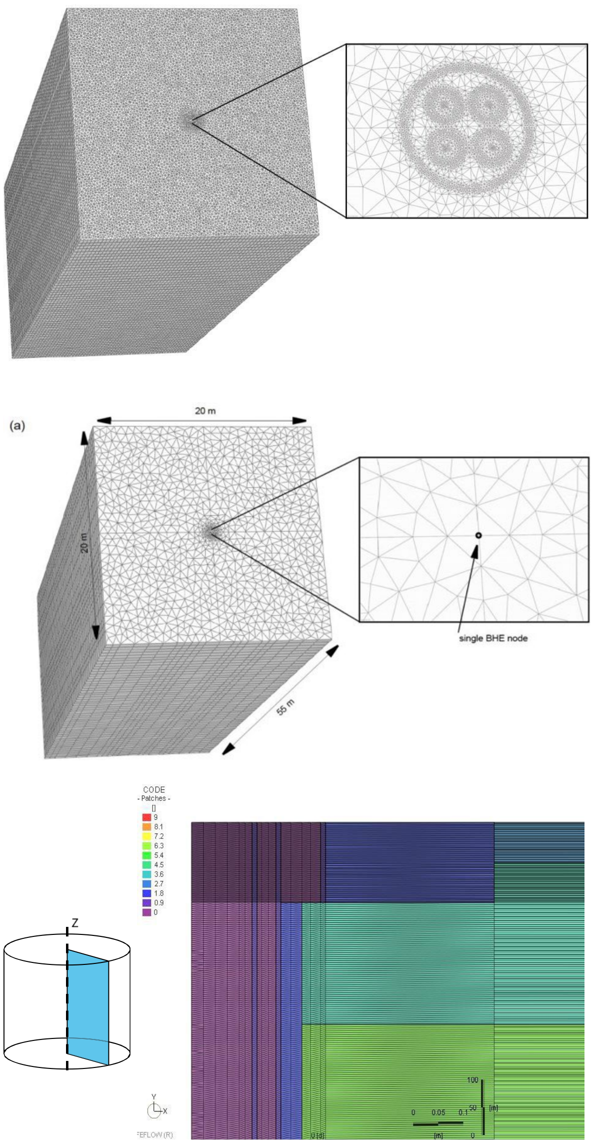

Figure 2: Example of mesh for a BHE, using explicit 3D full discretization of the BHE (top), with the BHE embedded as a 1D element (middle) and 2D mesh with vertical axisymmetric geometry (bottom)

This approach reduces drastically the number of elements and thus decreases computation time (several days for a 50-year simulation). However, it remains only partially suitable for optimization problems. In the case of coaxial BHE, FEFLOW offers a third modeling option using a 2D vertical axisymmetric geometry, where the axis of rotation corresponds to the vertical axis (Fig. 2, bottom). This approach significantly reduces the number of mesh elements —and thus computation time. It is the method used for the comparative simulations described later in this paper. Nevertheless, even with this simplified geometry, a 50-year simulation requires several days of computation, limiting its suitability for optimization tasks.

3.2 Analytical approach

The FEFLOW-based approach allows for the simulation of any type of configuration, but it requires a high degree of discretization and long computation times. The initial attempts made in the context of this study highlighted the difficulty of applying such methods for optimization problems, especially when key parameters are still poorly known. In fact, the mesh must be recreated each time the geometry is modified. For this reason, complementary alternative solutions were sought. A new analytical approach was developed by Perrochet (2021) based on differential equations derived from the principles of mass and heat conservation.

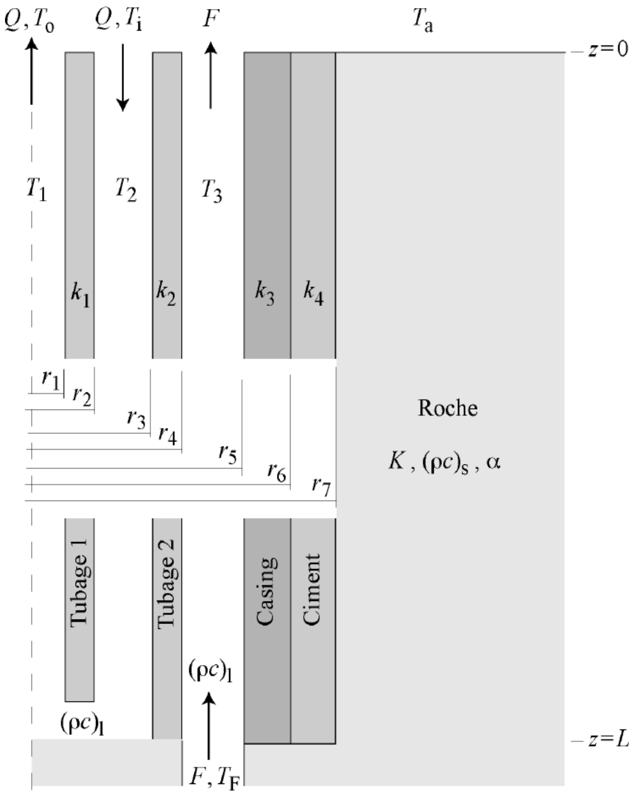

Figure 3: Schematic representation of the hybrid coaxial BHE, where a hydrothermal artesian flow (*F*) occurs between the tubing and the casing

This approach enables very fast computation times but requires a higher level of simplification, such as the linearity of processes, the homogeneity of the parameters, longitudinal 1D advective heat transport in the BHE and 1D radial heat exchanges with the environment, instantaneous thermal equilibrium within the BHE and constant flow rate (Fig. 3).

The approach consists in defining the heat budget for the three components (descending fluid, ascending fluid, and hydrothermal component) using individual differential equations and solving the system by coupling the three equations. The temperature profile in the three domains area $T_1(z)$, $T_2(z)$ and $T_3(z)$ must each satisfy a differential equilibrium equation between an advective term associated with an upflow - or downflow - and a conductive exchange source term between neighboring domains (Perrochet, 2021). For the central upstreaming tube, the temperature profile $T_1(z)$ is governed by:

$$-Q(\rho c)_l \frac{dT_1(z)}{dz} = \frac{2\pi k_1 (T_2(z) - T_1(z))}{\ln\left(\frac{r_2}{r_1}\right)} \qquad [1]$$

where Q is the flow rate within the BHE. For the annular downstream tube, the temperature T2(z) is governed by:

$$Q(\rho c)_l \frac{dT_2(z)}{dz} = -\frac{2\pi k_1 (T_2(z) - T_1(z))}{\ln\left(\frac{r_2}{r_1}\right)} + \frac{2\pi k_2 (T_3(z) - T_2(z))}{\ln\left(\frac{r_4}{r_3}\right)} \qquad [2]$$

The hydrothermal component (F) undergoes mutual heat exchange with the fluid circulating in the descending annulus (domain 2), and with the surrounding rock through the circular bilayer composed of the casing and the cemented zone. The heat flux from the surrounding rock is approximated with a hydrodynamic analogy—that of the 'flow rate of an artesian well' (Perrochet 2005). The temperature $T_3(z)$ is governed by:

$$-F(\rho c)_l \frac{dT_3(z)}{dz} = -\frac{2\pi k_2 (T_3(z) - T_2(z))}{\ln\left(\frac{r_4}{r_3}\right)} + \frac{2\pi K (T_a + \alpha z - T_3(z))}{\frac{K}{\bar{k}} \ln\left(\frac{r_7}{r_5}\right) + \ln\left(1 + \sqrt{\frac{2Kt}{(\rho C)_s r_7^2}}\right)} \qquad [3]$$

with

$$\bar{k} = \frac{ln\left(\frac{r_7}{r_5}\right)}{\frac{1}{k_3} ln\left(\frac{r_6}{r_5}\right) + \frac{1}{k_4} ln\left(\frac{r_7}{r_6}\right)} \qquad [4]$$

The differential equations are solved by applying the following conditions:

$$T_2(z=0) = T_1(z=0) - \Delta T \qquad [5]$$

$$T_3(z=L) = T_F \qquad [6]$$

$$T_1(z=L) = T_2(z=L) \qquad [7]$$

3 VALIDATION OF THE ANALYTICAL APPROACH

3.1 Validation without hydrothermal flow

To validate the newly developed approaches, a comparative analysis of all the above-described methods was conducted, where no hydrothermal flow circulation is considered (*F=0*).

For this purpose, a coaxial geometry based on the Thônex-1 borehole and a defined parameter set were used. The injection temperature over 50-year simulation is shown in Figure 4.

All approaches are comparable except the FEFLOW model using the BHE as embedded 1D element. The good agreement between the analytical approach with the hybrid model EWS and the fully discretized 3D FEFLOW model indicates the suitability of the analytical approach for simulation with no hydrothermal circulation.

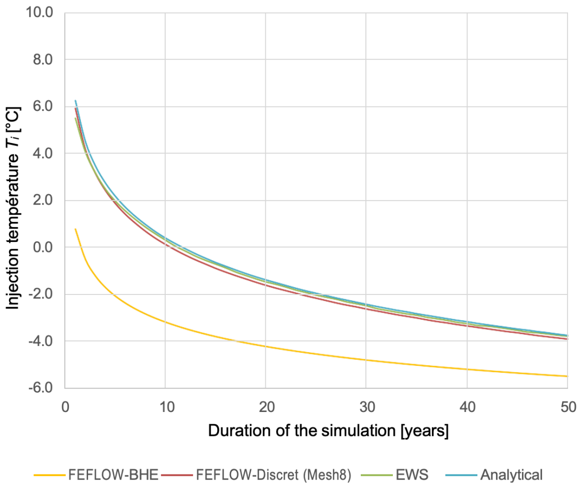

Figure 4: Comparative analysis of the injection temperature T_i using the the different modelling approaches.

3.2 Validation with hydrothermal flow

For the simulation of the coaxial configuration without hydrothermal circulation, the hybrid approach EWS as well as the FEFLOW model using the BHE as embedded 1D element are no longer applicable. The simulations performed using the fully discretized 3D FEFLOW model and the analytical approach have been done for flow rates F = 0.2 l/s and F = 0.4 l/s. Both approaches give comparable results (Fig. 5), validating the analytical approach for further performance analysis and optimizations processes.

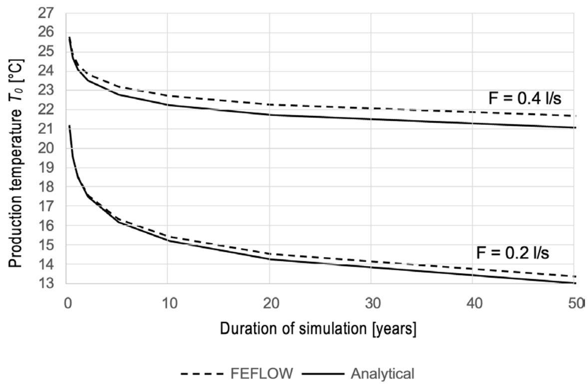

Figure 5: Comparison of the production temperature T_0 for two different hydrothermal flow rates (F) using the fully discretized 3D FEFLOW model and the analytical approach.

5. RESULTS

5.1 Sensitivity to hydrothermal component

The analytical approach was used to study the sensitivity of production temperature at well-head to the flow rate of hydrothermal component *(F)*. Without hydrothermal flow (*F=0* l/s) and considering an extraction rate of about 112 kW, the production temperature T_0 at well-head would drop to -0.63°C after 50 years of exploitation. With a hydrothermal component F = 0.1 l/s, the minimum temperature reaches +8°C, and with F = 0.5 l/s, it was around 24°C (Fig. 6). These results demonstrate a strong temperature stabilizing effect of the hydrothermal component. The combined use of the BHE (closed loop) with the hydrothermal component makes it possible to increase the thermal output while using the BHE in a sustainable manner.

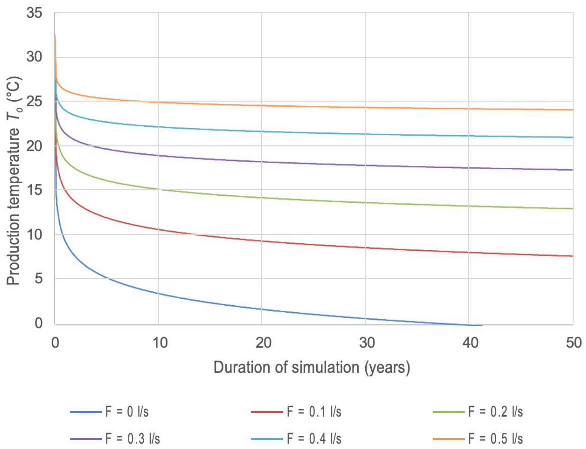

Figure 6: Sensitivity analysis of the well-head production temperature T_0 during 50 yrs of exploitation, considering different hydrothermal flow rate F. The thermal output remains constant at 112 kW.

5.2 Estimation of performance gain

An iterative method was used to determine the maximum extraction power for each hydrothermal flow rate (F), keeping the 50-year output production temperature at -0.63°C (Fig. 7).

For F = 0.1 l/s, the output increased from 112 kW to 144 kW (a 28% gain). At F = 0.5 l/s, output reached 246.6 kW, more than doubling the baseline value. Performance gains aligned well with the thermal contribution from hydrothermal flow.

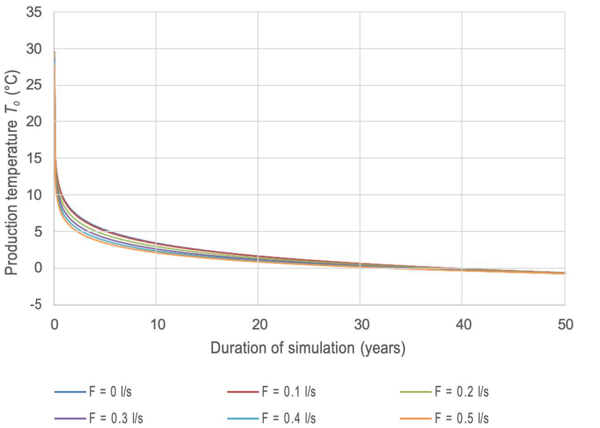

Figure 7: Comparison of the production temperature at well-head T_0 during 50 yrs of exploitation for different hydrothermal flow rate (F). For every scenario the extraction rate Q has been modified to obtain the same temperature after 50 yrs as for scenario with F=0.

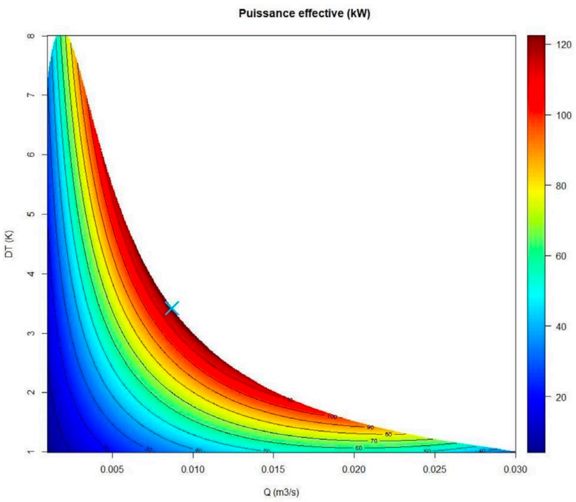

Figure 8: Estimation of the net extraction power in kW using the coaxial BHE with a hydrothermal flow circulation of F=0.03 l/s. The blue cross indicates the optimal pairing between the temperature differential and flow differential DT and flow rate Q.

6.3 System Optimization

Hydraulic losses due to fluid circulation with the coaxial BHE were considered to estimate the net effective power ($P_{eff} = P_{thermal} - P_{loss}$).

For F = 0.03 l/s, the optimal net power is 122.4 kW at Q = 8.7 l/s and ΔT = 3.42 K (Fig. 8).

For F=0 l/s, the optimal net power was 109 kW at Q = 8.65 l/s and ΔT = 3.08 K, showing a 12% net gain with artesian input.

5. CONCLUSIONS

The simulations conducted within this project demonstrated that a 1800 m deep coaxial BHE installed in an existing hydrothermal well can provide a thermal power of 100–150 kW when the hydrothermal flow is not used.

Integrating heat extraction from the artesian hydrothermal flow circulating along the BHE significantly enhances system performance, while enabling a thermal recharge of the environment and thus a sustainable use of the BHE. For example, a hydrothermal flow rate of just 0.1 l/s increases the heat extraction power from 112 kW to 144 kW, representing a 28% performance gain.

A newly developed analytical approach closely matched results from the hybrid model EWS and the fully discretized 3D FEFLOW simulations, while significantly reducing computation time. This enables rapid sensitivity analyses and system optimization. The method can support future deployments in similar retrofit contexts, including oil and gas wells.

The Thônex-1 geothermal retrofit showcases the technical and economic viability deep coaxial systems in underperforming hydrothermal wells or depleted O&G boreholes. The results provide compelling evidence for deploying such systems in marginal hydrothermal fields.

The concept offers scalable integration potential within low-carbon heating strategies. Beyond Geneva, this approach can be replicated across Europe, including in decommissioned oil and gas infrastructure, supporting the EU Green Deal's goals for sustainable geothermal development.

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