A New Deep Geothermal Concept Based on the Geyser Principle

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Keywords: close-loop geothermal, deep drilling, downhole heat exchangers, fractureless EGS

ABSTRACT

When fracking is not allowed, or considered to be insufficient to lead to economic circulation rates in a conventional EGS system, drilling for geothermal energy exploitation in hot hard rock becomes futile, unless alternative concepts are investigated. One such alternative is offered by closed-loop geothermal systems, which do not require hydraulic stimulation to harness geothermal energy.

This proposed closed-loop concept is based on the Geyser principle, which has several advantages compared to conventional deep borehole exchangers. In particular, no downhole lifting is needed to run the system, which eliminates the costs of operating and maintaining pumps, and also the risk of well downtime when the pumps present issues. A Geyser produces high-enthalpy superheated steam, which can then be used to drive directly the power plants, without an additional heat exchange cycle.

The challenge of such a system is represented by the fact that certain downhole conditions must be attained for it to work efficiently. The boiling point of each liquid depends significantly on both temperature and pressure, which in turn depend on well location and depth. Thus, temperature and pressure are key design parameters.

The novelty of the system consists of a downhole boiler with a custom-designed entry valve. Due to the hydrostatic column of water in the annulus, the pressure is relatively high at the boiler’s inlet, i.e. ~1 bar/10m. The valve controls the inlet of the boiler according to a predetermined pressure value. This mechanism leads to low pressure within the boiler and, consequently, to a lower boiling temperature. As the surrounding hot rock heats up the fluid within the boiler, any remaining liquid after the initial flash through the valve transitions to steam. The superheated steam has significantly lower density than liquid and will therefore flow from the boiler up the tubing to surface without the need for artificial lift, and at greater rates.

1. INTRODUCTION

Various solutions for unconventional deep geothermal exploitation have been proposed in the literature, some of which have already been implemented in the field. They have been prompted by the need to design methods suitable to situations where the heat is there, but not the permeability and/or the porosity of the formation. These solutions include:

- The original Hot Dry Rock concept (Potter et al., 1974) and its derivations, based on the creation of hydraulic connectivity between injection and production wells, or injection and production legs of the same borehole (Gedzius and Teodoriu, 2011) (see Figure 1).

- Single-well (open) concepts relying on different sections of the well connecting to a production and to an injection layer, isolated from one another – e.g. the Genesys Concept (Tischner et al., 2010).

Both concepts above rely on fractures to provide the necessary contact area for the pumped fluid to gain heat underground. When hydraulic stimulation is not allowed, or considered to be insufficient to lead to economic circulation rates, alternative concepts are required.

- Single-well (closed) concepts, where the fluids circulating in the borehole do not get in contact with the surrounding formation. Here, it is assumed that sufficient heat can be transferred from the formation to the wellbore, despite the significantly smaller contact area compared to that achievable via fracturing. On the other hand, such systems can be more attractive in terms of reduced geological/reservoir risk (no direct fluid–rock interaction) and also reduced costs (one well only). One such example is the system proposed by Duerden (2011) and depicted in Figure 2, which is claimed to operate under the principle of thermo-siphon, resulting from the different densities of the circulating fluid(s) at different depths, depending on its temperature. As a result, fluid flow is established without the need for pumping (although a low-power pump is included as a back-up in the design). Note that this concept was devised to provide a solution to geothermal heat production.

The last category also includes solutions with in-well heat exchangers. One design based on downhole steam generation has been proposed by Lakic (2010), with the following downhole assembly: a boiler, a turbine, an electric generator, a condenser and an electric cable. A schematic representation of the Self Contained In-Ground Geothermal Generator (SCI-GGG) is shown in Figure 3.

1
One Well Concepts
- Genesys-Typ
- gebo-multilateral with multifracs
- gebo-lateral through faults

Two Well Concepts
- Horizontal wells
- Fishtail

Figure 1. Various methods to connect the geothermal reservoir, after Gedzius and Teodoriu (2011)

Figure 2. The single-well concept proposed by Duerden (2011)
2. THE PROPOSED CONCEPT

Geyser s are hot springs where the steam naturally comes to surface due to the rock temperature underground exceeding the boiling point of water. Commonly, geysers work intermittently, as they need some recharging time.

The closed-loop concept presented in this paper is based on the geysers’ principle. Differently from other deep geothermal concepts, it requires neither hydraulic stimulation of the reservoir, nor fluid pumping. Also, differently from the solution depicted in Figure 3, it does not rely on generating electricity in the well itself, but rather works on the geysers concept of high-enthalpy, superheated steam flowing naturally to surface. There, the steam can be used to drive directly the power plant. On the other hand, this system requires certain pressure and temperature conditions for it to work, as it will be discussed in what follows. Placing all the generators at surface reduces the investment and maintenance costs.

This concept is described in more detail by Heller and Teodoriu (2013).


The proposed system consists of a downhole heat exchanger (herein called ‘boiler’, since it changes the water phase from liquid to steam) with a custom-designed inlet valve capable of controlling the admission pressure into the boiler. From surface, water is let into the wellbore annulus space between production casing and tubing, without pumping. The inlet pressure to the boiler is therefore equal to the hydrostatic column of the water in the annulus, i.e. ~1 bar/10 m. At the selected depth, depending on the geothermal gradient of the region, there will be a corresponding downhole temperature. The valve controls the inlet pressure within the boiler, such that it reduces the saturation point of the water (note that the boiling point of a liquid depends significantly on pressure). Isenthalpic flash evaporation can be assumed to occur through the valve; at lower pressure, the high-temperature water contains more energy than required to achieve saturated water conditions, and the enthalpy made available when the pressure is reduced will evaporate part of the water into steam. The fraction of steam generated during the flash depends on the liquid enthalpy upstream and downstream of the valve.

The boiler itself is heated up by the surrounding rock. If the flash evaporation through the valve leads to 100% steam, then the steam can become superheated as it travels further through the boiler. On the other hand, if the flash into steam is only partial, then the remaining liquid can gain heat as it travels through the boiler, with associated flow boiling. The latter phenomenon is strictly dependent on the design of the boiler.
The exiting superheated steam has low density, therefore generating a much lower hydrostatic pressure compared to water, and will flow to surface through an insulated tubing (to minimize re-condensation) without the need for downhole pumping. The level of superheating and the circulating flow rate must be designed so that they ensure single-phase steam conditions all the way to surface. It is anticipated that - during the initialization of the process - steam could become wet within the tubing, leading to two-phase flow. Under these initial transient circumstances, the pressure in the boiler would be adjusted accordingly, until sufficient heat transfer has occurred and a steady-state scenario is reached.

The working principle of this proposed concept is illustrated in Figure 4.

![Figure 4](image)

**Figure 4. The proposed deep geothermal concept based on the Geyser principle (Bierenriede, 2011)**

The temperature of the rock on depth varies with geographical location, and it is difficult to predict the actual temperature at a certain depth when no equally deep well has been drilled in that given area before. The large differences in the temperature distribution worldwide can be shown by comparing different geothermal projects, as shown in Figure 5.

![Figure 5](image)

**Figure 5. Temperature vs. depth (Germany [Kehrer, 2003] and worldwide [Huenges, 2007])**

Even when the temperature comparison is limited to one country, like Germany, the temperature gradient varies between 20 to 100°C/km (Kehrer, 2003). Only a limited amount of temperature data is available for the deep sections, leading to greater inaccuracy of temperature predictions (>50°C), which would have an impact on the performance of the boiler concept.

As already mentioned, the valve at the inlet of the boiler is a key element that ensures the functionality of the process. It is necessary to reduce the pressure of the incoming water from the annulus and, as a result, its boiling point. The reduced boiling point allows the production of steam even at temperatures as low as 200°C. The valve isolates the boiler from the hydrostatic column in the annulus, so that the temperature of the entering working fluid is reduced to the boiling point depending on the boiler working pressure only. The working pressure is defined by the vertical lift performance of the tubing. If the pressure in the boiler is such that
the water remains in the liquid state, then a small temperature increase will be observed, as shown in Figure 6 (all enthalpy values are calculated according to Bertsch GmbH&Co., 2011).

Downstream of the valve, heat transfer between formation and fluid within the boiler will depend on the temperature differential, independently of pressure. Naturally, the higher the enthalpy of the fluid entering the boiler, the lower the heat transfer required within it.

The interdependencies between inlet and outlet temperature, pressure and enthalpy allow the design of different scenarios. In Figure 7, different enthalpies and temperatures are shown, together with the required heat transfer rates to run the system (Bierenriede, 2011). The deeper the well, the higher the temperature (and therefore the enthalpy) of the fluid in the annulus space.

In this example, a flow rate of 7 kg/s is assumed, resulting in a thermal energy content of the steam at surface of approximately 20 MWth. If the enthalpy of the fluid entering the boiler is 883 kJ/kg, an additional 14.18 MWth of thermal energy are necessary to achieve the required final enthalpy of 2984 kJ/kg. On the other hand, a fluid with at 350°C necessitates of only 9.58 MWth to be transferred to the boiler. The enthalpy of the produced fluid must be in the range of 2830 to 3000 kJ/kg, corresponding to 100% steam, which is a precondition to run the system successfully.

Scenario 1 represents the situation when the inlet temperature of the fluid is lower than the required output temperature. In this case, the process is be as follows: through the valve, flash evaporation takes place, leading to steam (possibly wet) at a temperature of 300°C. The flash is possible because the boiling temperature of water at 60 bar is 275.6°C. Due to the boiler construction, the generated steam will then reside in the boiler for a certain interval of time, allowing it to overheat till the desired value of outlet temperature.
Scenario 2 refers to the situation when the inlet temperature is higher than the output temperature. In this case the residence time in the boiler can be reduced, since the flashed steam already has the required temperature. Assuming that field implementation of this concept is initiated by filling the annulus with water and waiting till temperature stabilization along the well, scenario 2 would represent the starting phase of the geothermal exploitation process, while scenario 1 would represent the steady-state situation after initial fast cooling of the surroundings.

3. ENHANCED HEAT FLOW

As previously mentioned, the heat transfer between surrounding rock and boiler is crucial to establish superheating conditions for the exiting steam and/or for ensuring 100% steam conditions. When heat transfer is expected to be slow, the boiler must be designed in such a way that the contact time between the working fluid and the hottest zone of the well is maximized. In case of temperature gradients below 35°C/km, careful boiler design will help increase the heat exchange area and therefore maximize the temperature of the working fluid. An open hole or a contingency casing could be a solution after the setting shoe of the 9-5/8” casing. It is assumed that the tubing is insulated and placed in this section. Consequently, the working fluid has the opportunity to gain extra temperature by travelling through an even deeper section and having longer residence time in the boiler.

Figure 8a shows a potential configuration for a vertical well, with the insulated tubing and the open hole section for enhanced heat transfer between rock and working fluid. This solution may use a much smaller well diameter below the boiler to enhance the heat inlet temperature. It is a cost efficient solution for the first wells.

Figure 8b shows a potential configuration for a horizontal well. In this case, the surrounding temperature is constant along the horizontal section and no insulation is needed for the second tubing in this area. A simple pipe injects the working fluid directly to the bottom of the well. Then the fluid is heated up as it flows towards the boiler, using the well length to increase the resident time. This alternative provides more space in the horizontal section and longer heat-up time due to the absence of lower vacuum-isolated tubing, see Fig. 8a (left). Most importantly, the horizontal section can be cased and cemented, therefore ensuring no contact between working fluid and rock.

Figure 8. Increasing contact time using a vertical (left) and a horizontal well (right) construction (after Bierenriede, 2011)

5. DISCUSSIONS

As shown above, the proposed concept does not require hydraulic stimulation of the reservoir rock, as it is assumed that the heat transfer around the wellbore is sufficient.

Table 1 shows a comparison between the EGS project at Soultz-sous-Forêts and this proposed concept, in terms of contact area between rock and circulation fluid, downhole temperature (actual, for Soultz-sous-Forêts, and required, for this concept) and corresponding net output.

Table 1. Comparison between the Soultz-sous-Forêts project and the proposed Geyser concept

<table>
<thead>
<tr>
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<th>Soultz-sous-Forêts</th>
<th>Proposed Geyser Principle *</th>
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<tbody>
<tr>
<td>Heat Exchange Area</td>
<td>~3,000,000 m² (BINE, 2009)</td>
<td>270 m²</td>
</tr>
<tr>
<td>Temperature of Rock</td>
<td>200 °C (Hettkamp et al., 2004)</td>
<td>300 – 400 °C</td>
</tr>
<tr>
<td>Net Output (expected)</td>
<td>4.5 MW (Hettkamp et al., 2004)</td>
<td>2 MW</td>
</tr>
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* Calculated for a 530-m long boiler, with and OD of 0.162 m
Preliminary calculation (Bierenriede, 2011) have shown that the concept will work as long as the inlet temperature is high enough to generate steam at the given depth. The outlet pressure of the superheated steam is what controls the boiling point of the steam. Typically, the outlet pressure will vary between 60 and 100 bar (with an estimated wellhead pressure between 40 and 70 bar). Under these conditions, the minimum inlet temperature for the boiler must be higher than the boiling temperature at 60 bar, i.e. 275.6°C. With a geothermal gradient of 40°C/km, this can be achieved at depths below 7000 m.

Since the contact area between fluid and rock is limited to 250-300 m², a risk of rapid cooling of the near wellbore region exists, which may require drilling several wells in the same area (as per the “geothermal well farms” concept) and produce them in rotation. Another alternative is to drill the fish tail well concept, using alternatively the left and right branches to extract the heat, as illustrated in Figure 9.

The proposed concept can also be applied as a “Magma Probe” solution, where the well is drilled directly into a magma chamber and the boiler is placed there. As no fluids will interact with the magma (during the heat mining period), this process would be more environmentally friendly (being closed-loop) than current field implementations. The main advantage of such Magma Probe is that the temperature could reach more than 500°C for longer time. At the time of writing, little information is available on magma-wellbore heat transfer characteristics.

6. CONCLUSIONS

This paper presents a closed-loop geothermal system that does not require hydraulic stimulation to harness deep geothermal energy.

The concept is based on the Geyser principle, with no downhole lifting requirements. A Geyser produces high-enthalpy superheated steam, which can then be used to drive directly the energy power plants.

The challenge of such system is its technical feasibility in relation to downhole pressure and temperature conditions, wellbore construction and boiler design.

Under its present status of development, this concept requires further investigations to assess the actual heat flow from the rock to the working fluid and the overall efficiency and cost-effectiveness of the process.

Preliminary estimations (Bierenriede, 2011) suggest a relatively low overall heat transfer rate for this closed system, in the range of 2.26 MWth to 7.55 MWth. In comparison, 13 MWth could be generated in Soultz-sous-Forêts with an underground heating path of 600 m between injection and production at ~5000 m depth. However, conventional HDR/EGS projects require multiple wells to be drilled, in combination with stimulation to create the required hydraulic communication. Also, in comparison with conventional HDR/EGS projects, this concept would require significantly lower circulation rates (7 kg/s compared to the 35 kg/s or higher), with associated longer contact time downhole and zero risk of induced seismicity.

ACKNOWLEDGMENT

The authors would like to thank Mr. Lars Bierenriede for his commitment to this topic during his MS thesis work, and for his extensive calculations.
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