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Closed-Loop Geothermal in Steam Dominated Reservoirs

Brian Higgins, Joseph Scherer, Alvaro Amaya, Harish Chandrasekar, and Andrew Van Horn

GreenFire Energy Inc.

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ABSTRACT

A recent GreenFire Energy research breakthrough has led to the application of closed-loop technology in steam dominated geothermal reservoirs, including high enthalpy two-phase reservoirs. This application of closed-loop geothermal (CLG) is called Steam Dominated GreenLoop (SDGL). In SDGL a downhole tube-in-tube heat exchanger is used to circulate large volumes of a working fluid (e.g., water, supercritical CO_2, iso-pentane). The working fluid returns to the surface hot through a vacuum insulated tube and can be flashed to produce power at an existing power plant, used for the direct production of power by an integrated Organic Rankine Cycle (ORC) power-generating system, or used for district heating. Downhole, steam condenses on the surface of the heat exchanger, transferring its latent heat of vaporization to the working fluid. The condensed steam produces a flow of liquid condensate towards the bottom of the well, where it builds up to produce the hydrostatic head required to force the liquid deep into the reservoir. Non-condensable gases are allowed to slowly rise to the surface, where they are collected and treated. The effect of the down-hole closed-loop heat exchanger is to extract heat, rather than mass, from the steam dominated resource, thereby conserving water and maintaining pressure in the geothermal resource. The system effectively pumps water through the deepest and hottest portion of the reservoir, which returns to the upper reservoir as steam. In this paper, we will present modeling results showing key steps in the process.

1. Introduction

The ideal geothermal resource contains abundant heat and available high-enthalpy, high-pressure steam that can be used to produce renewable electric power but only a small fraction of recoverable geothermal heat can be retrieved with conventional hydrothermal technology [Tester et al., 2006]. Commonly in current geothermal systems, much of the steam exiting the turbine is condensed and this condensate is then used in the cooling-water loop; mostly vaporizing and is lost to the atmosphere [Robertson, 1978]. This results in more water being extracted from the resource than is returned [Goyal, 1999; Brophy et al, 2010; Stark et al, 2005]. This, in turn, leads to a degradation in the field's performance over time [Sanyal et al.,2011].

A solution to the problem of geothermal resources losing production potential over time due to water loss is simply to never extract water from the resource. GreenFire Energy has developed a closed-loop geothermal technology that extracts heat only and retains 100% of the water in the resource. This technology was demonstrated, in part, at the Coso Geothermal Field by using a down borehole heat exchanger (DBHX) [Higgins et al., 2019; Amaya et al., 2020; Scherer et al., 2020]. A variation of this technology has also been developed to extract heat from deep wells in hot, dry rock [Higgins et al., 2016; Oldenburg et al., 2016]. The Coso demonstration was critical to acquire verification data to support the process modeling efforts within GreenFire Energy.

Beyond water and resource conservation, GreenFire Energy's closed-loop geothermal approach also has other eco-friendly characteristics (no waste streams, no contact with subsurface water, minimal visual and noise pollution, renewable, etc.) that make it one of the most favorable renewable energy technologies from a lifecycle environmental perspective. Similar to other geothermal approaches, the system is largely subsurface and hence has a relatively small land footprint and does not impact wildlife. However, while conventional geothermal systems perform well on environmental characteristics, the closed-loop approach is better since:

a) there is no separate reinjection of fluids that can cause seismic or subsidence events,
b) there is no mixing of subsurface fluids with the working fluids or interference with natural flows in the resource that would negatively impact nearby landowners or their businesses (e.g., farming or hot springs resorts), and
c) there are no waste streams associated with mineralization (e.g., H_2S) in the geothermal brine.

2. The DBHX Closed-Loop Technology

GreenFire Energy's down-borehole heat exchanger, or DBHX, is a tube-in-tube assembly tailored to specific resource characteristics installed deep into a geothermal well. This well can be an existing geothermal well or it can be a purpose-drilled well designed for maximum power production. The DBHX is installed in the well and is supported by the wellhead. Depending on the particular project, the wellhead may be configured to allow geothermal fluids to be coproduced, as well as in and out flows of the DBHX working fluid. Working fluids can be water, supercritical carbon dioxide (sCO_2), or a variety of other refrigerants, which are modeled and selected based on their thermodynamic characteristics relative to the resource temperature, pressure, and permeability, as well as the feed zone productivity.

The DBHX in a SDGL system consists of a liner inserted into the well with a plugged end at the lowest point. The geothermal fluid in the resource is allowed to flow around this liner and only non-condensable gases (NCGs) are allowed to be produced to the surface, where they are treated and emitted, or reinjected. Inside this plugged liner, extending nearly its entire length, is installed a coaxial vacuum insulated tube (VIT). As shown in Figure 1, the working fluid is introduced to the annular region between the VIT and the liner and is circulated by pumping to the bottom of the DBHX. The working fluid extracts heat from the flow of geothermal fluid entering the well near the bottom of the DBHX. The temperature of the DBHX fluid is kept low enough to cause the geothermal steam to condense on the relatively colder DBHX surface. The rate of steam condensation can be improved by designing DBHX surface features such as fins or channels. See Figure 1 for an example schematic of the arrangement of the SDGL DBHX in the well.

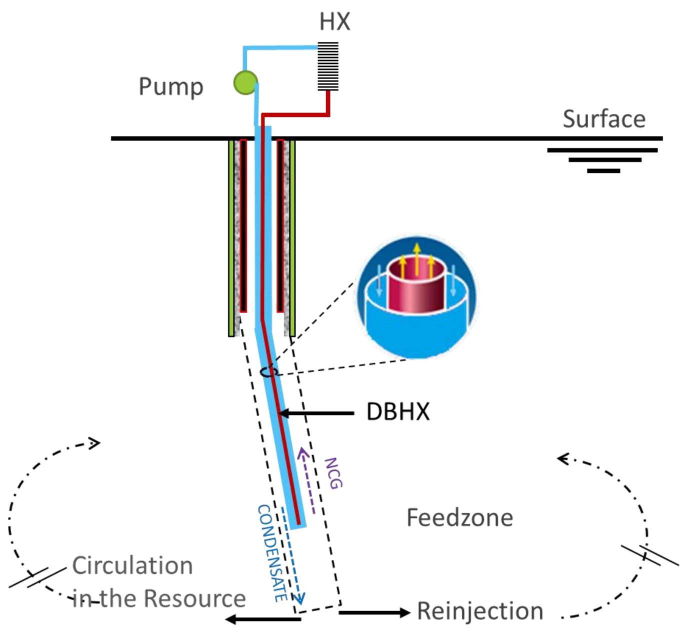

Figure 1: The DBHX is located in a well, hung from the wellhead. The black arrows indicate the inlet/outlet of the geothermal fluid. The blue arrows show the flow of the condensate deep into the well. The purple arrow shows the slow production of NCGs to the surface.

3. Closed-Loop Process Flow Description

The closed-loop process flow can be simply described as follows: a pump is used as the motive force within the DBHX. Generally, the flow is down the annular portion of the DBHX on the outside of the VIT. At the bottom of the DBHX, the flow reverses direction and returns up the center of the VIT. Outside the DBHX, the steam enters the wellbore and interacts with the cold surface of the DBHX. This causes the steam to quickly condense to liquid. The liquid (by virtue of having ~1000x the density of steam) will flow downwards, while the uncondensed steam and NCGs will slowly flow upwards.

The DBHX working fluid flows counter to the NCGs, which are vented at the surface. Due to the counter flow, as the NCGs approach the surface, they cool and lose humidity until they are produced relatively dry at the surface. NCGs may be treated (e.g., H_2O_2 for H_2S abatement) and then vented or reinjected.

Power production occurs by using a heat exchanger with an ORC binary power plant. Other alternatives include flashing water to an existing power plant or using an ORC fluid (e.g., CO_2 or iso-pentane) in the DBHX to generate power directly at the surface. GreenFire Energy's proprietary models can analyze and design systems tailored to each specific resource.

The selection of a site with the correct geothermal geological properties is important to optimize performance. There should be sufficient reservoir pressure, enthalpy, and permeability to provide a good flow of steam to the wellbore. Ideally this occurs from a feed zone that is relatively shallow (e.g., a steam cap). Additionally, there should be a lower feed zone or resource permeability that is near the bottom of the well. These features are evaluated using drilling logs, well surveys, injectivity and productivity tests, and other geothermal techniques.

4. Process Modeling

The process modeling takes four individual approaches and brings them together to produce a performance prediction. First, the well feed zones are evaluated using well data and a well flow model. Second, an iterative approach is used to evaluate the power production potential at different wellbore pressures. Third, the DBHX and wellbore annulus are modeled to account for friction and heat transfer to produce net power predictions. Fourth, surface equipment is modeled to predict power performance. Additionally, GreenFire Energy is developing a resource model to evaluate the recirculated flow within the resource. Each of these is described below in subsections 4.1 to 4.5.

4.1 Well Flow Modeling

After data collection, the first step in the SDGL evaluation is to produce a feed zone productivity index that relates the primary feed zone productivity (flow rate) to the well bore pressure, the resource pressure, and the permeability of the feed zone.

The wellbore model, based on mass and energy balance, flow regimens, and feed zone characterization, calculates the feed zone flow into the wellbore and calculates the well pressure that satisfies the governing equations, using these inputs combined with wellbore geometries and the roughness of casing/liners. Additionally, the temperature profile and thermal parameters of the surrounding rock can be assumed to account for conductive heat loss.

4.2 Conservation of Energy Modeling

Once the productivity of the primary feed zone of the well is established, we use a conservation of energy approach to relate the thermal enthalpy available from the condensation of the steam to the heat absorption potential of the DBHX working fluid. Implicit in this formulation is that the condensation of the steam onto the cold DBHX surface can only happen at its saturated temperature and pressure; that is, it must be two-phase near the surface of the DBHX. This allows us to couple the DBHX temperature to the steam condensation temperature, which fixes the well bore pressure. This wellbore pressure is used with the feed zone productivity index calculated above to determine the steam inflow.

As the DBHX fluid flow rate (in the model and in the well) is increased or decreased, the temperature of the outside surface of the DBHX is inversely affected, which in turn affects steam flow into the well which we also calculate. Hence, by changing the flow rate of the working fluid through the DBHX we can also control the inflow of steam to the well bore.

At the same time, we are able to control the wellhead pressure. If the wellhead pressure is lower than the condensation pressure near the feed zone (minus column weight and friction losses [Haaland, 1983]), the steam will move up the well bore before it condenses. Likewise, if the wellhead pressure is higher than the condensation pressure near the feed zone, the steam will not condense, and the DBHX fluid will not heat up (thus dropping the temperature/pressure at the feed zone).

The above effects are stable and reenforcing. As such, we expect that control of the down borehole flows will be easy to do from the surface by controlling the flow of the fluid through the DBHX and the well head pressure as the NCGs are vented.

4.3 DBHX Closed-Loop Flow Modeling

Once all of the above has been modeled, the DBHX flow is modeled taking into account the heat transfer across all of the surfaces, so that the amount of heat transfer surface required by the DBHX is correctly evaluated. This model, as described below, has been developed internally and details have been published elsewhere [Fox and Higgins, 2016; Higgins et al., 2016].

Our model takes into account conservation of mass and energy and includes isentropic compression and expansion as the working fluid moves up or down the well. Friction is accounted for in the well using a Darcy friction factor via the Haaland equation [Haaland, 1983]. Friction manifests itself in the model as pressure drop. Heat transfer is modeled as 1D conduction through solid sections and as convection to fluids using a Nusselt number calculated with the Dittus-Boelter equation [Bergman, 2011]. Gas and liquid properties are called from the NIST database using CoolProps [Bell et al., 2014].

A one-dimensional, finite-volume, steady-state implicit solution scheme is used to solve the equations described above (similar to the Euler Method). For each small length interval, the "next" position is calculated using two thermodynamic variables from the previous length interval, from which all other thermodynamic variables are calculated using the current position. By using a sufficiently small length interval, this solution method converges to the implicit solution. The well and DBHX are modeled using 800 intervals.

There are three flows to be considered: the downflowing closed-loop fluid, the upflowing closed-loop fluid, and the geothermal fluid. The boundary conditions are defined for the inlet of each of the three flows according to temperature, pressure and flow. Heat transfer from the geothermal brine to the working fluid in the closed loop, as well as through the VIT (between the upflow and downflow working fluid) is also considered. Because the upflowing closed-loop fluid conditions are equal to the exit conditions for the downflowing closed-loop fluid (as the fluid "turns the corner"), the solution requires iteration.

Generalized results from this modeling framework are presented in the following figures. In Figures 2a through 2f, the DBHX flow conditions are shown. The top three figures, with water as the working fluid in the DBHX, show the inlet (D1), DBHX bottom (D2), and outlet (D3) thermodynamic conditions relative to the vapor dome on a T-s diagram (2a), P-v diagram (2b), and a P-h diagram (2c). In the bottom three figures, the temperature (2d), pressure (2e), and enthalpy (2f) of the water inside the DBHX are plotted versus depth. In all cases, the water inside the DBHX remains a liquid; that is, there is no flashing to steam due to the downhole pressure inside the DBHX. The geothermal flow points, labeled G1 to G7, represent the various positions within the resource or within the well, as described in the figure inset. Considering Figures 2def, the geothermal fluid as it approaches the well (G2) is colder than the resource temperature (G1) due to expansion from the resource pressure to the well pressure. This is also shown in Figure 2e. The steam, continuing to flow upwards to G3, loses enthalpy to the DBHX and significant steam condenses to liquid water, flowing downward due to density. Deep in the well, the liquid water has a surface (G4) and builds hydrostatic pressure to the bottom of the well (G5). So long as the pressure at G5 is higher than the resource pressure plus the required injection pressure (as a function of the lower well permeability and injectivity potential), the liquid will reenter the resource at the bottom of the well. The NCGs that cannot condense, continue to flow upwards (above G3) to the wellhead.

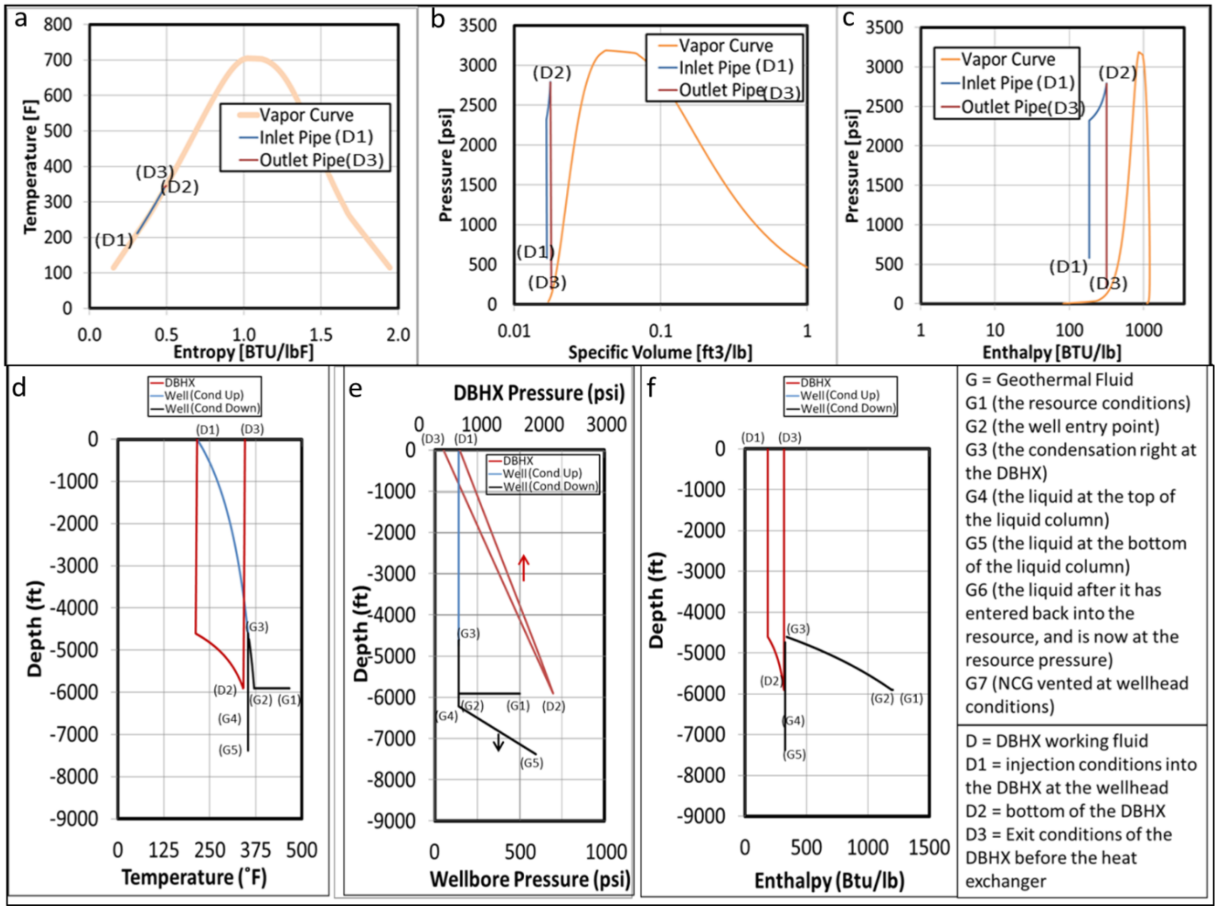

Figure 2: Typical DBHX modeling results.

4.4 Surface Equipment

When an ORC is envisioned to be connected at the surface, various other calculation methods are used to design and optimize the ORC system to increase net power production, minimizing the parasitic power losses due to pumping the DBHX working fluid, the ORC working fluid, and the heat rejection system. Figure 3 shows a typical analysis using commercial software to model the ORC system, integrated with inputs from the above modeling to optimize ORC net power. As a secondary layer to this analysis, we also consider costs in our optimization scenarios.

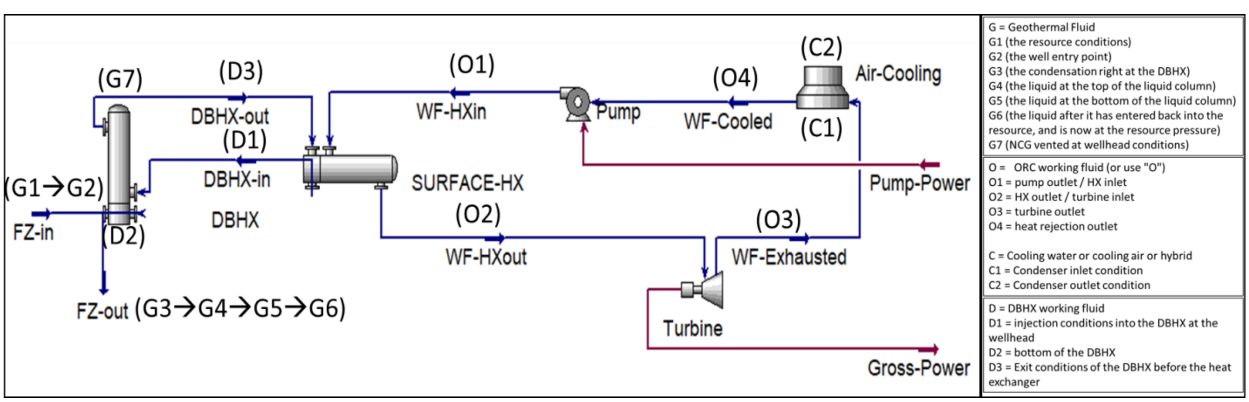

Figure 3: Modeling to optimize the ORC design and performance.

4.5 Reservoir Flow Modeling

The flow through the reservoir in a vapor dominated system such as The Geysers was modeled using COMSOL Multiphysics [COMSOL, 2019] finite element simulator. The condensation of the reservoir fluid in the DBHX causes a hydrostatic pressure buildup in the bottom of the well. In the model results shown in Figure 4, the fluid is assumed to quickly vaporize as it flows again into the reservoir from the well bottom to the upper parts of the DBHX system; that is, only the vapor phase has been modeled. The well bottom hence acts as an injector with a mass flow rate and the bottom of the DBHX acts as a producer. The simulation results presented are for a well bottom at 4 km and temperature of 260°C and the fluid is produced at the end of the DBHX of total length 1.2km from the surface. The injection from the bottom was assumed to be equal to the production at 10 kg/s and the flow streamlines were studied for 2.4 months of continuous operation to produce the streamlines plotted in Figure 4. The results suggest that even after the condensate has vaporized, the steam does not immediately return directly back to the steam cap, and instead, it moves throughout the reservoir. Large fractures were not modeled and simulating their effect is a topic of future interest.

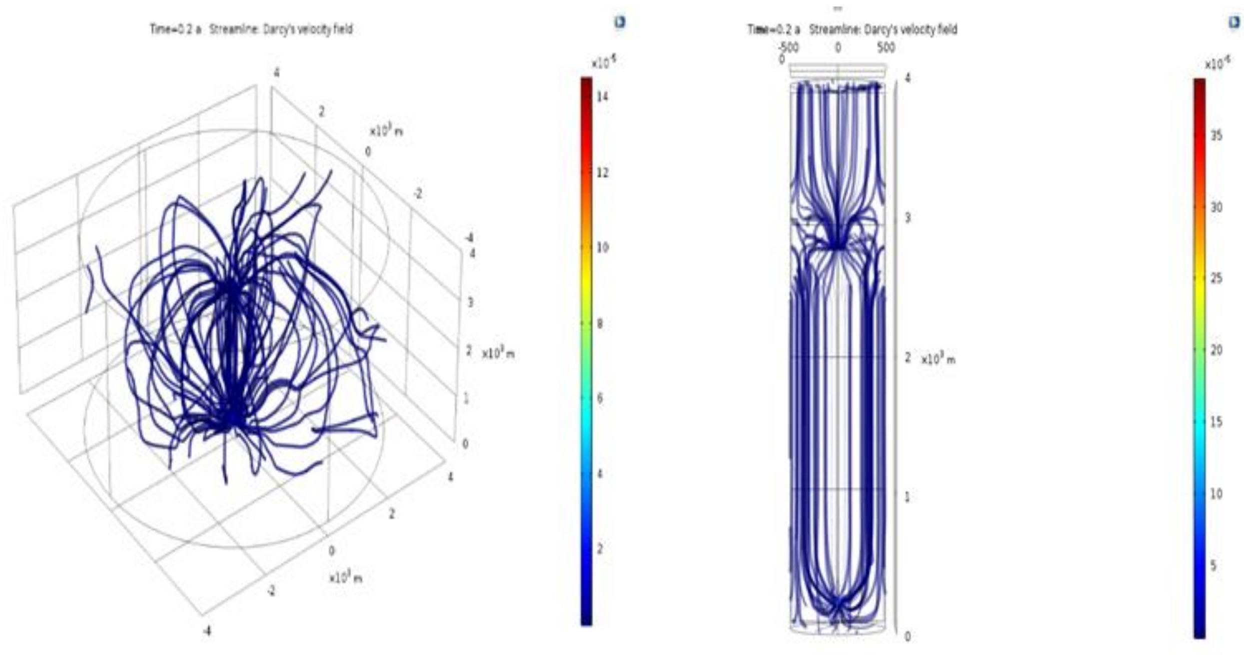

Figure 4: Finite Element Reservoir Modeling. The left figure represents 100 streamlines assuming a 4 km radius reservoir at the end of 2.4 months of continuous operation and the right figure represents multiple streamlines of prominent magnitudes assuming a 500 m radius reservoir at the end of 2.4 months of continuous operation.

6. Conclusions

GreenFire Energy has developed a closed-loop geothermal (CLG) energy system consisting of a down borehole heat exchanger placed into a well, which can produce significant power without consuming or removing any water from the geothermal reservoir. This technology is applicable to any geothermal reservoir capable of producing steam (wet or dry). The performance evaluation combines well flow modeling, conservation of energy, integrated surface system modeling, and a proprietary 1D flow model.

7. Future Work

Reservoir Modeling

GreenFire Energy is working with partners to develop a realistic two-phase flow model similar to the results shown in Figure 4, but with the following improvements. First, both the liquid and vapor phases will be modeled, including the phase change as the fluids move through the resource. Second, a realistic reservoir fracture network will be included in the modeling to better determine the fate of returning geothermal fluids reentering deep into the resource, transitioning to steam, and then flowing upwards to repopulate the steam cap.

High-Enthalpy Two-Phase Reservoir Application

The results and analysis presented above have been for a dry steam reservoir indicative of The Geysers. We have also modeled fields throughout the Pacific Rim, where the reservoirs typically do not have dry steam and generally have two-phase flow. For these analyses, we use the same process described in this paper, but a portion of the geothermal fluid that is produced to the well contains liquid. Preliminary analysis suggests that the physics of SDGL still work to preserve resource fluid and pressure for long term sustainability. So long as the well has sufficient depth accompanied by a primary shallow feed zone and existing permeability at the bottom of the well, the analysis shows significant power potential is available and can be achieved at attractive levelized costs of energy.

For both steam dominated and two-phase reservoirs, we have successfully applied for global patents covering this exciting new technology. Shown in Figure 5 is the patent sketch, provided as additional insight into the process.

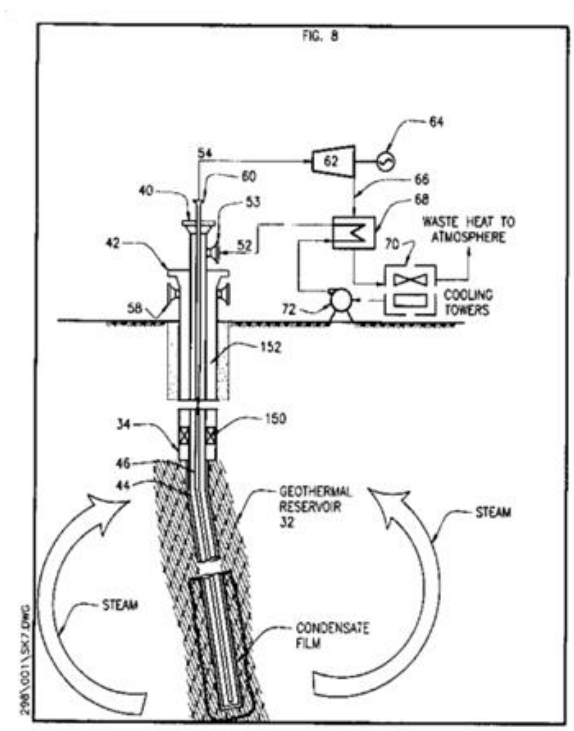

Figure 5: Patent application image

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