GreenFire Energy Closed-Loop Geothermal Demonstration at the Coso Geothermal Field

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Keywords

Closed loop, Geothermal Retrofit, Demonstration

ABSTRACT

GreenFire Energy has demonstrated a downhole, closed-loop geothermal technology at the Coso Geothermal Field. In this demonstration, water and CO_2 were each circulated through a tube-in-tube heat exchanger placed 330 meters down the well, hung from the wellhead. At the same time, various production rates of geothermal steam were simultaneously produced. The primary goal of this demonstration was to verify GreenFire Energy's process modeling assumptions and to illustrate the power production potential of closed-loop geothermal technology.

1. Introduction

Many geothermal wells are drilled and then left unused to generate power. This may be due to a number of reasons including poor brine production, high non-condensable gases (NCGs), low wellhead pressure, corrosive brine, insufficient resource permeability, etc. For many of these wells, there is substantial power production potential. GreenFire Energy has demonstrated how a down-borehole heat exchanger (DBHX) can be used to rehabilitate idle wells. At the Coso Geothermal Field, located in eastern California, the target well has the potential to produce several megawatts of power, but is not used due to high NCGs. This project was also intended to demonstrate the potential of closed-loop geothermal systems in new projects that extract enthalpy from deep wells in hot, dry rock. Verification of GreenFire Energy's modeling will help the future development of approaches to retrofit existing hydrothermal wells to become productive and to plan and build full-scale, closed-loop geothermal projects using wells drilled into hot, dry rock.

2. The DBHX Closed-Loop Technology

A down-borehole heat exchanger, or DBHX, is simply a tube-in-tube assembly installed into an existing well. The DBHX is hung from the existing wellhead. Modifications to the wellhead are provided so that the working fluid can be introduced into the DBHX. Working fluids can be

water, supercritical carbon dioxide (sCO_2), or other refrigerants. The DBHX consists of a liner inserted into the well with a plugged end at the lowest point. The geothermal resource is allowed to flow around this liner and may be produced to the surface. Inside the plugged liner, a vacuum insulated tube (VIT) is installed, extending nearly to the bottom of the liner. The working fluid is circulated to the bottom of the DBHX. The flow direction of the working fluid can be selected depending on the characteristics of the working fluid. The working fluid extracts heat from the flow of coproduced geothermal fluid rising in the outer annulus between the well casing and the DBHX (Figure 1).

The DBHX is designed to remove enthalpy from the geothermal resource as it is produced. The chief advantage of the DBHX is that the working fluid is exposed to the higher brine temperatures located near the bottom of the DBHX relative to the exit of the well (at the surface). As such, the working fluid can reach the surface at a higher temperature than the produced geothermal brine. When water is used as the working fluid in the DBHX, the net effect is to produce steam that does not contain NCGs. Similarly, when sCO_2 is used as the working fluid, the sCO_2 is heated and available to make power directly.

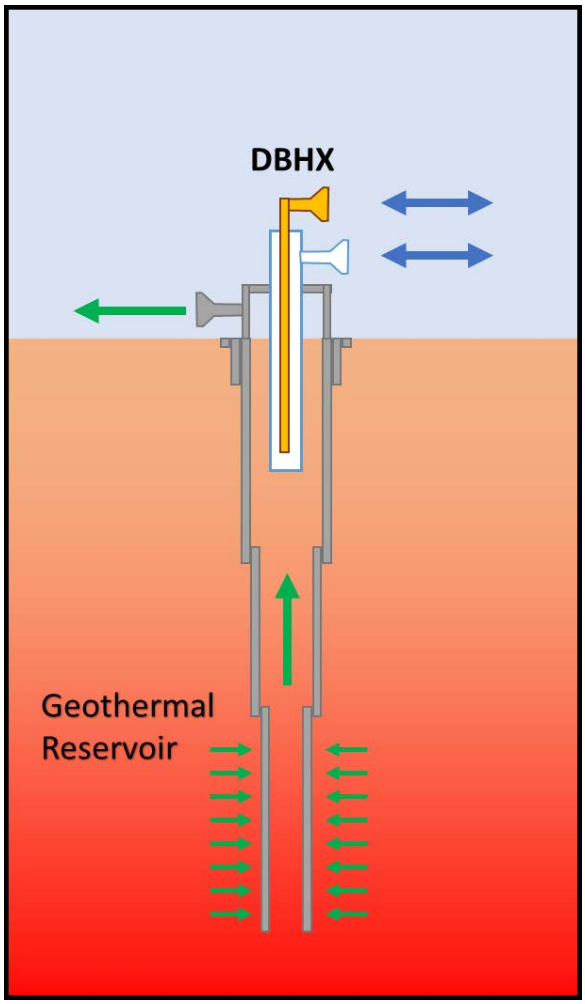


Figure 1: A schematic showing the DBHX. The blue arrows indicate the inlet/outlet of the DBHX fluid (which can flow either direction). The green arrows indicate the flow of geothermal brine to the surface around the DBHX.

3. Experimental Process Flow Description for Water Flow

In Figure 2, a process flow diagram (PFD) is shown for water as the working fluid in the DBHX. The flow direction for water in the DBHX is (1) down the annular portion of the DBHX, and (2) up the center of the VIT. By flowing in this direction, the water flows counter to the geothermal brine, thus maximizing the water production temperature and enthalpy extraction from the geothermal brine. Exterior to the DBHX, a repurposed silencer is used as a water holding tank. Water is circulated from this tank, through the DBHX, and returns to the tank. A portion of the returning water flashes to steam at atmospheric pressure. Since the steam is removed from the loop, makeup water is required to maintain water level in the tank. A small portion of the tank water is blown down to the sump to reduce salinity buildup. The makeup water is equal to the portion of steam generated plus the small flow of blowdown.

Two parameters can be varied in this arrangement: (1) the flow rate of geothermal brine produced to the other silencer (using PCV 1) and (2) the flow rate of water through the closed-loop system (using PCV 2).

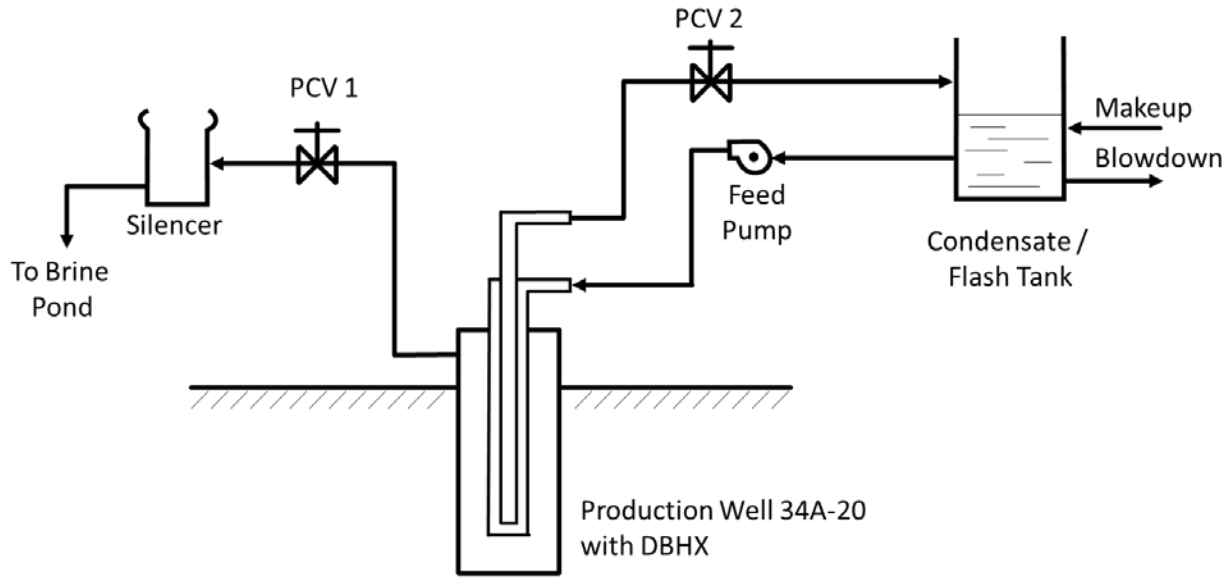


Figure 2: The DBHX process flow diagram for water as the working fluid.

The flow of geothermal brine to the silencer (though the pressure control valve, PCV 1) was analyzed for (1) flow rate of steam, (2) flow rate of brine, (3) NCG content in the steam, and (4) chloride and sodium content in the brine. From this data and pressure, the enthalpy can be deduced.

The flow of water through the closed loop is provided by the feed pump and the flow rate is controlled by the downstream PCV 2. The circulating water generally flashes across PCV 2. A small portion of blowdown is controlled (~5 GPM), and makeup water is added to maintain an appropriate level in the water tank.

4. Process Modeling for Water as Working Fluid

4.1 Surface Equipment Modeling

The above-ground surface equipment comprises a turbine, heat rejection, and feed pump or compressor. The turbine and compressor are modeled using isentropic efficiency assumptions. Heat rejection is generally modeled using either ambient air or an evaporative water-cooling system. Heat rejection, in either case, is heavily dependent on the ambient weather conditions (temperature, pressure, and humidity) and these factors are considered in the process modeling.

4.2 Closed-Loop Modeling

We use a 1-D process model built in MS Excel to model the steady-state, closed-loop flow. This model takes into account conservation of mass and energy, and includes isentropic compression and expansion as the water 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). Heat loss to the overburden is not considered. Gas and liquid properties are called from the NIST database using CoolProps, an Excel plugin.

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 explicit solution. For the data presented in this paper, the well was modeled with 100 intervals, 23 of which contain the DBHX.

There are three flows to be considered: the downflowing closed-loop fluid, the upflowing closed-loop fluid, and the coproduced 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. More details can be found in our previous works (Fox and Higgins, 2016; Higgins et al., 2016).

Additionally, a principal component analysis (PCA) and Bayesian statistics modeling techniques were applied to the experimental data obtained in this study to optimize an objective function of power production to determine the optimal operational variables for specific closed loop and brine well flows. This power production function has been contrasted and validated by using a coupling between the thermodynamic 1-D process model system equations and a Monte Carlo simulation methodology to produce a statistic modeling forecast of the optimal variable conditions expected in a "virtual test".

5.0 Results for Water as the Working Fluid

Data are presented below for the closed-loop DBHX flowing with water while producing the well in May, 2019. The well was cycled through three different production rates: low, medium, and high (described below). Likewise, the closed loop was circulated with three different circulation rates: low, medium, and high, which correspond to approximately 41, 74, and 133 kph of produced fluid. NCGs averaged 23% by weight of the produced flow. Not all possible variations of these conditions were investigated. In the end, six combined flow conditions were investigated (four of which had simultaneous well flow rate and enthalpy measurements).

Table 1: Well and closed-loop test conditions

Test Number	Well Flow	Closed-Loop Flow	Enthalpy Testing
1	High	High	Yes
2	High	Medium	No
3	High	Low	Yes
4	Medium	Low	No
5	Medium	Medium	Yes
6	Low	Medium	Yes

5.1 Well Flow Data

In December 2017, a well flow test was performed before the DBHX was installed. In Figure 3, the measured wellhead pressure (WHP) and wellhead temperature (WHT) are plotted using closed symbols versus the total well flow rate. Also plotted in Figure 3 (as open symbols), are the WHP and WHT data corresponding to the test conditions in Table 1 during DBHX testing. The red open diamonds in Figure 3 represent the closed-loop DBHX water exit temperature for the corresponding well flow conditions. For every case, the water returning from the well is at a higher temperature than the geothermal brine exiting the well. This is because the geothermal brine and closed-loop water flow counter-current to each other (with the water returning to the surface from the bottom through a vacuum insulated tube).

Figure 4 shows the demonstration equipment during testing when both the well and the closed-loop DBHX were flowing. In the figure, the wellhead is in the center of the photo, with the inlet and outlet of the closed loop at the top of the wellhead. The vessel on the left is the closed loop water holding tank. The vessel on the right is the well silencer. The blue water tanks in the background are used to store freshwater, used for makeup water.

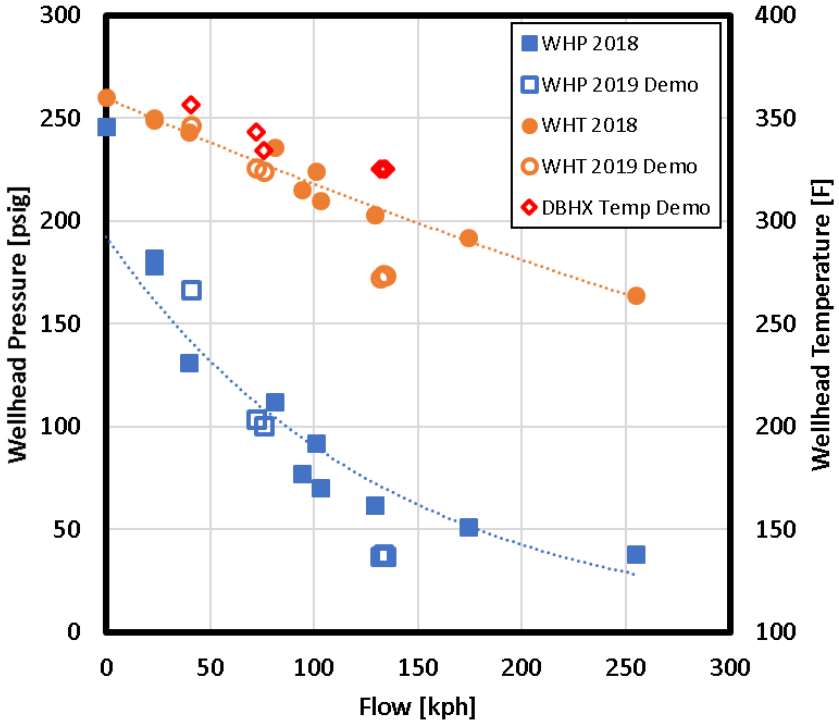


Figure 3: Wellhead pressure, wellhead temperature, and DBHX outlet temperature plotted versus total well flow.



Figure 4: Photo of the demonstration equipment just after the well was opened.



Figure 5: Photo of the demonstration equipment.

In Figure 5, the view of the installation taken looking the other direction (the photo was taken from the top of the blue water tanks shown in Figure 4 while the system was not in operation). Much of the foreground of this photo is equipment required for the circulation of sCO_2, which was also tested, but is outside the scope of this paper. The silencer in the upper right is the water holding tank that holds the water circulating inside the closed loop. Seen at the base of the water tank from right to left: (1) the blowdown line to the sump, (2) the feedwater pump inlet, (3) the level indicator, and (4) the return two-phase flow line to the silencer. The feedwater pump is not seen in the image because it was installed below the surface to account for net positive suction head (NPSH) inlet pressure requirements for the pump. The closed-loop water path is clockwise in the picture, from the tank to the well, then back around to the closed-loop water control valve (PCV 2). PVC 2 can be seen at the top of the image just to the right of the wellhead. All of the equipment on the left side of the concrete pad is for sCO_2 (air compressor, chiller, feed pump, blower, heat exchanger, and water PCV for cooling).

5.2 Well Flow Data with Closed-Loop DBHX

For the four tests points in Table 1 where enthalpy testing was simultaneously performed (Tests 1, 3, 5, and 6), the change in enthalpy to the closed-loop working fluid can be compared to the change in enthalpy of the geofluid. The reason this can be done is that the liquid measured in the well flow had virtually no dissolved solids. This indicates that the well was producing steam and NCGs only, and that the measured liquid is steam condensed by the flow. Simply taking the latent heat of vaporization multiplied by the measured liquid flow exiting the well, yields enthalpy extraction of 8.9, 7.5, 9.0, and 9.2 MW for tests 1, 3, 5, and 6, respectively.

At the same time, the closed-loop water flow rate was measured, as was the inlet temperature and pressure. Before the control valve (PCV 2), the closed-loop flow throughout is always a liquid. The enthalpy increase in the closed-loop flow is a simple calculation of the specific enthalpy difference entering and leaving the closed loop multiplied by the flow rate, which are calculated as 9.4, 7.6, 10.4, and 11.3 MW for the same four tests, respectively. The average deviation between these data points and the ones in the paragraph above is 10%, which is reasonably close.

Although the experiment uses an atmospheric pressure silencer as a holding tank for the recirculated water, it is simple to determine the amount of steam that would be produced at the Coso steam gathering system pressure. At the exit of the DBHX, the water pressure is well above the saturation pressure for the produced temperature. This means that the DBHX water is 100% liquid. As such, the enthalpy can be calculated using temperature and pressure only. To determine the flashed quantity at the Coso gathering system pressure, the quality is then calculated using the same enthalpy and the gathering system pressure. For the Coso low pressure turbines, about 30 kph of steam produces one megawatt of electricity. The power predictions are plotted in Figure 6 versus the wellhead temperature. Note that there is a parasitic power loss attributed to the feedwater pump that is not included in the data of Figure 6 and is ~130 kW.

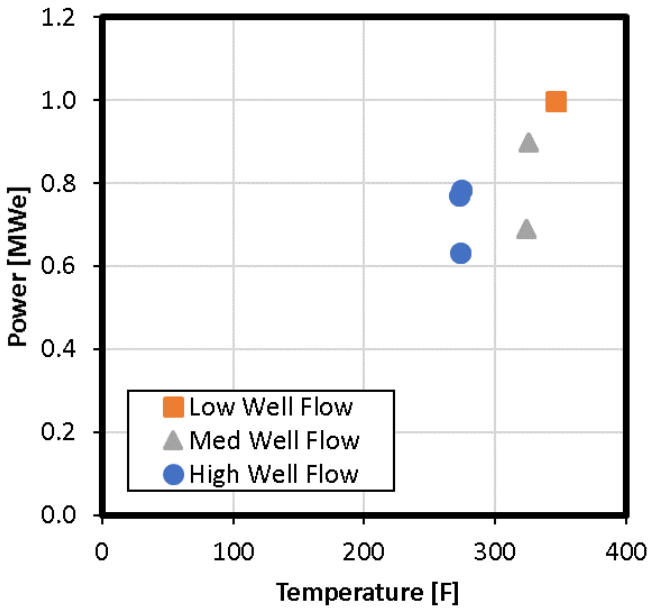


Figure 6: Electric power production potential for the DBHX water flashed to LP steam plotted versus wellhead temperature.

As expected from the modeling, and as clearly shown in Figure 6, more power is produced when the rate of coproduced geothermal fluid is reduced. This raises the temperature of the geothermal fluid that meets the closed-loop downhole heat exchanger, allowing the heat exchanger to absorb more heat.

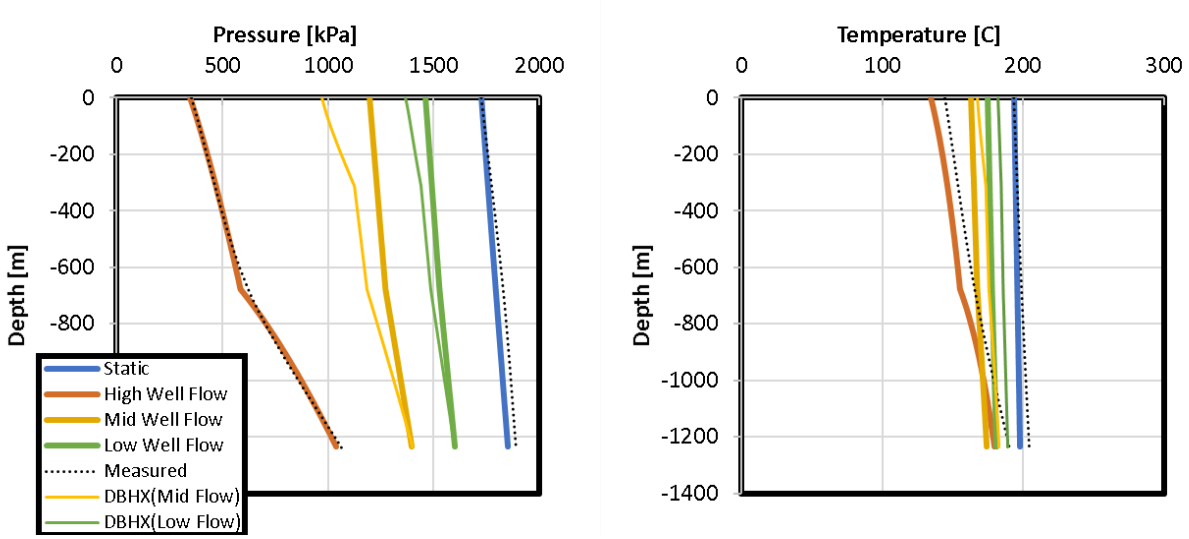


Figure 7: Temperature and pressure versus depth (modeled and measured data).

5.3 Well Flow Modeling

In December 2017, during the well productivity testing, downhole flowing and static surveys were performed without the DBHX in place. The measured downhole temperature and pressures are plotted in Figure 7 as dotted lines. As expected, both the temperature and pressure are lower when the well is flowing.

Also, in Figure 7 are modeled downhole temperatures and pressures for several well flow conditions corresponding to the conditions in Table 1 (high, medium, and low well flow). The bold orange line ("High Well Flow") is the modeling data that corresponds to the flowing well survey. Both the temperature and pressure follow the measured values. Likewise, the bold blue line ("Static") is the modeling data that corresponds to no flow being produced by the well. Again, both the downhole temperatures and pressures closely match the measured values.

For the mid- and low-flow cases, only surface temperature and pressure were measured and the plotted data in Figure 7 represent modeled data only. The thin lines of the same color are for the same flow rates, but with the DBHX installed. The DBHX creates more pressure drop in the well and this is seen as a higher change in pressure from the bottom of the well to the exit of the well (for the same flow).

For each of the well flow conditions in Table 1, the closed-loop flow was modeled while also modeling the geothermal flow. Figure 8 shows one such condition, where the closed loop has the flow corresponding to "Test 4" in Table 1. The light red line shows the modeled conditions with the closed loop in operation. This data can be directly compared to the yellow line (Mid Well Flow) data modeled using the same well flow, but without the closed-loop heat exchanger. The bold black lines in the right image in Figure 8 are the temperature within the DBHX, slowing increasing temperature as the water flows downward and constant temperature as it is extracted through the VIT.

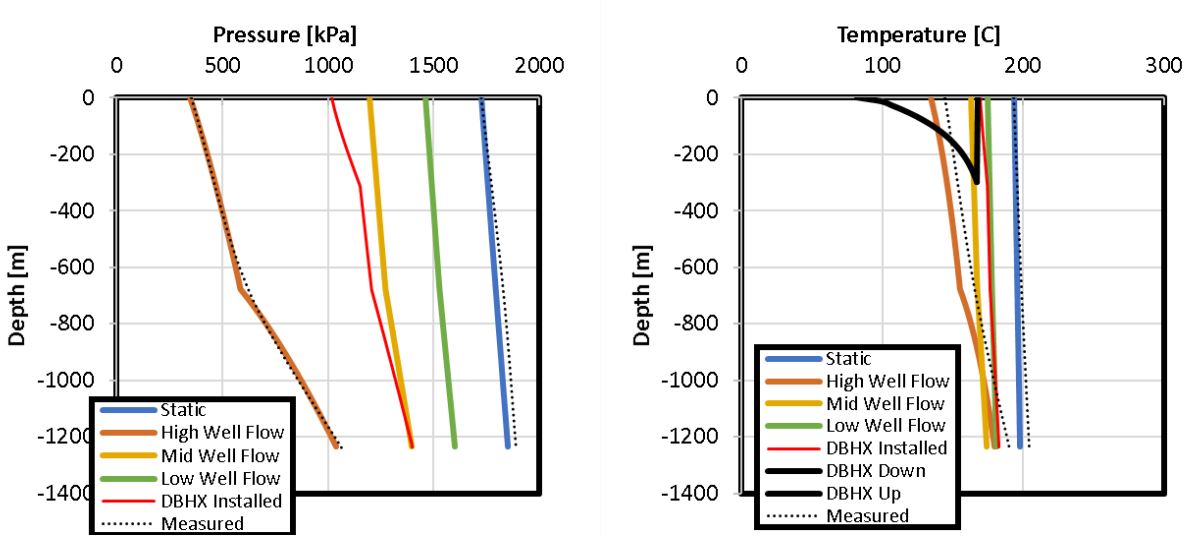


Figure 8: Temperature and pressure versus depth with the DBHX modeling for one test case.

Also, it is noteworthy that the differences between the thin yellow line in Figure 7 (with no flow in the DBHX) and the thin red line in Figure 8 (with DBHX flow) are minimal, as it is largely the steam quality of the well flow that is changing the most (not pressure or temperature).

In Figure 9, the quality of each flow of brine, using the same color scheme as for Figure 8, is plotted versus depth. This figure shows that in all cases the brine flow leaving the well is nearly 100% quality (or dry steam). But with the closed-loop heat exchanger installed, the steam quality drops, markedly. The steam is converted to liquid water on the well side of the heat exchanger, and a matching enthalpy rise is occurring on the inside of the heat exchanger. By passing a large flow rate of water through the closed loop, a portion of this water is flashed to steam at the system pressure for each circulation. As discussed above, the portion of flashed closed-loop steam is roughly equal to the portion of condensed geothermal steam.

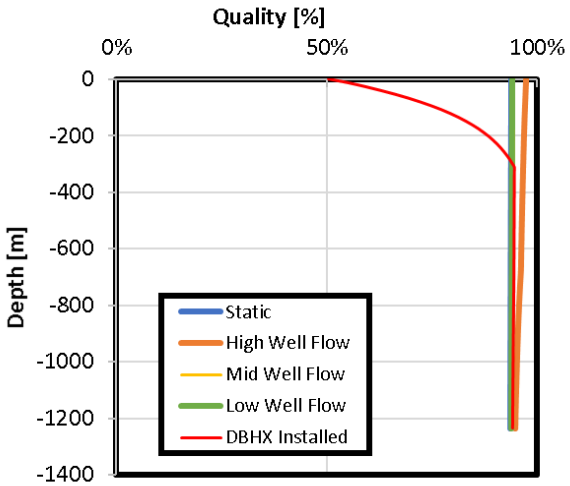


Figure 9: Steam quality versus depth (modeling only).

In Figure 10, the predicted power is plotted versus the measured power (as deduced by the quantity of steam produced by the working fluid for each test) for all six of the test conditions in Table 1. Also, the predicted closed-loop outlet temperature is plotted versus the measured temperature. The model inputs for each case only require the following information: the closed-loop water circulation rate, the closed-loop water inlet temperature, the well production rate, and wellhead pressure. The dotted lines in Figure 10 represent X=Y. The closer the data is to this line, the more representative the model predicts the measured results. Note that the power data plotted in Figure 10 does not include the parasitic power required for the pump, which is ~130 kW.

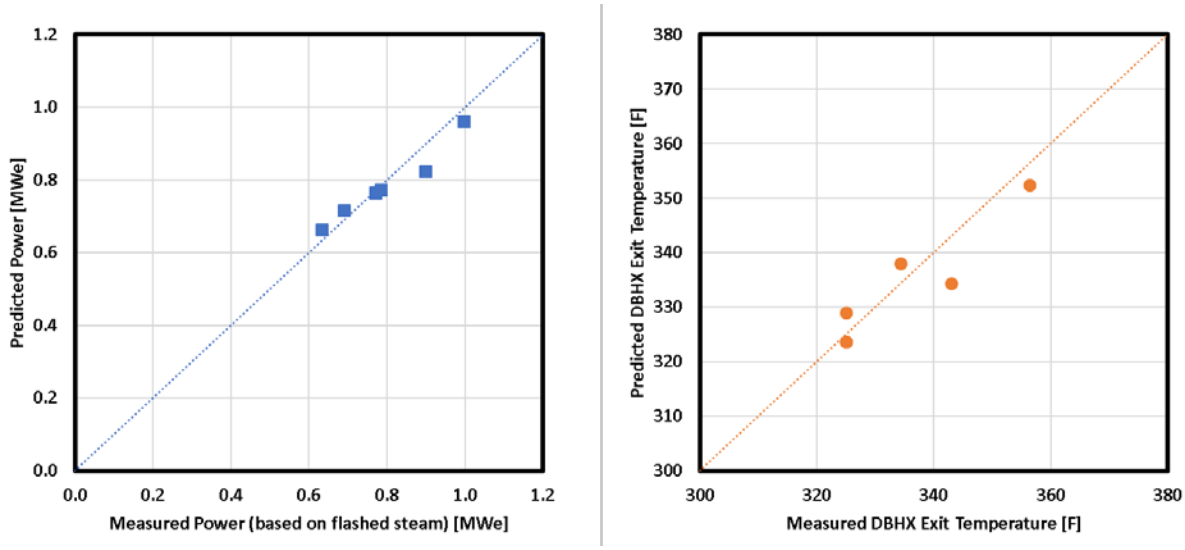


Figure 10: Electric power predicted by the model is plotted versus the measured power (left), and the closed-loop outlet temperature prediction is plotted versus the measured outlet temperature (right).

5.4 Statistic Modeling

Optimization of a geothermal power coproduction function for water as the working fluid has been obtained using a statistic modeling methodology with principal components (PCs) to support a principal component analysis (PCA), and using a Monte Carlo simulation.

PCA is a technique that transforms all the variables and all the experiments (observations) into dimensionless vectors and scores. The PC vectors create a new axis where the integrated information can be plotted and optimally analyzed.

Figure 11 is a biplot PCA schematic; it displays variables and observations analyses at the same time. Loadings and scores are plotted together on the same PC axes (defined by experimental flow rates) over the spatial domain (defined by power production in MW).

The statistical modeling process consists of five steps. In the first step, the six experimental sets of conditions (each represented by 18 operation variables) were analyzed. PC1 (61.2 % of variance) and PC2 (37.4 % of the variance) comprise 99% of all the information (see left and down axis in Figure 11).

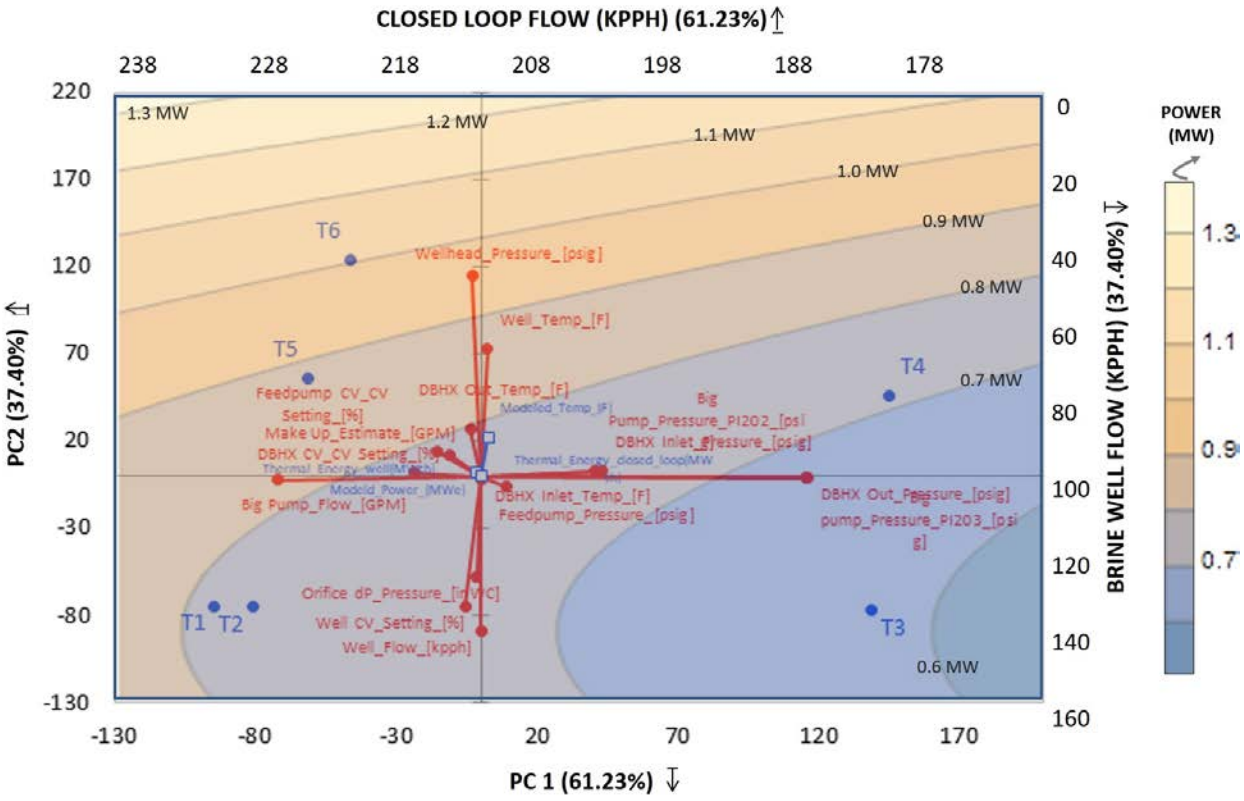


Figure 11: PC axis (left, down) transformed to flow axis (right, up), and energy output contours (MW) overlaying the source plot.

In the second step of the analysis, the PC axes are correlated with specific variables or processes to understand the orthogonal space where the variables and the experiments are placed as vectors (variables) and scores measured in testing (T1 to T6), respectively. This second step found that flows are the main variables that controls all the processes: PC1 is an inverse linear function of closed-loop flow and PC2 shows an inverse linear correlation to well flow (see right and up axis in Figure 11).

In the third step, the orthogonal dimensionless space is transformed through a power MW equation (in function of flows or PC axis). This source is overlain on the space in the biplot graph shown in Figure 11; it explains the position of experimental observations and variables orientation (vectors defined by its magnitude, direction and angles) related to power optimization direction.

The fourth step is an integral analysis that produces optimized values of variables for maximizing the power production function. The power source energy (over layered as a function of closed-loop flow and brine flow in Figure 11) produced less than 3% error in its estimation for all 6 experimental test conditions (T1 to T6).

The fifth step is forecasting the total power expected to be obtained by determining the “virtual test” conditions using two methodologies. Methodology 1 uses the objective power function shown in Figure 11 (considering 254 kph closed-loop water flow and 12 kph well flow), the electric power production result expected for this methodology is 1.3 MW. Methodology 2 uses

the 1-D thermodynamic closed-loop modeling equations (Section 4.2) enhanced by a Monte Carlo simulation methodology (considering 500 iterations in function of probability distribution of each variables) to validate the power forecasting of this “virtual test”. By considering the 18 optimized values of variables that maximize the power production found by PCA analysis, 1-D thermodynamic equations using Monte Carlo simulation methodology forecasts that the virtual test will produce 1.2 MW, with ±0.3 MW of interval at 50% of confidence. This result is shown in the probability histogram of the Figure 12. Both methodologies consider that virtual test conditions can increase power produced by about 20%.

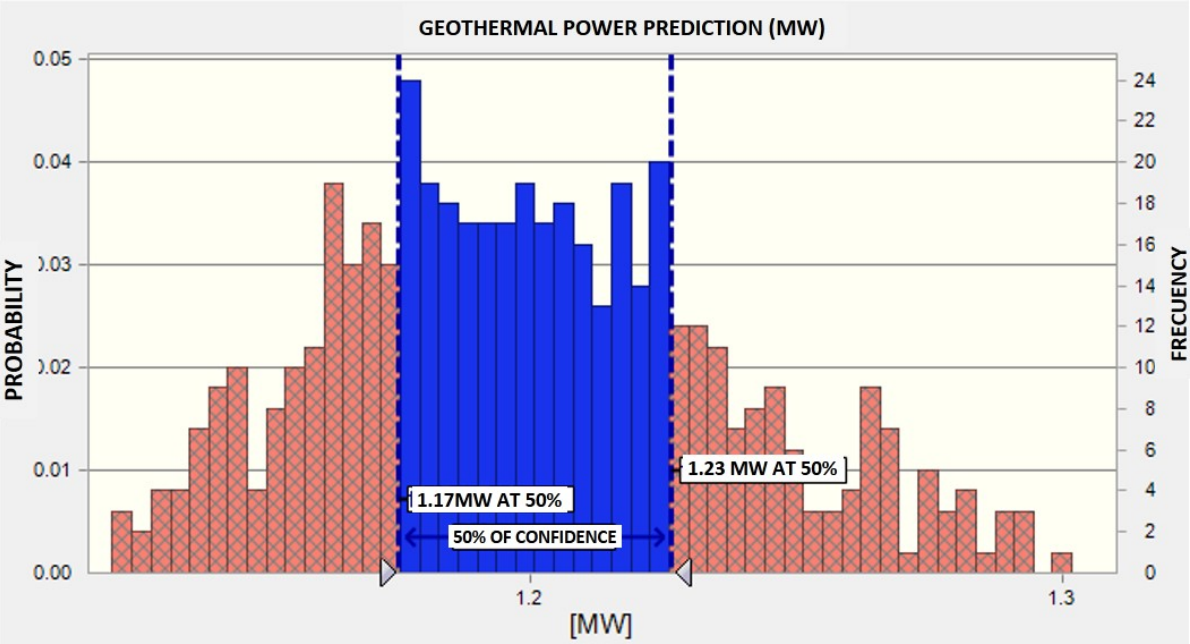


Figure 12: Power forecasting for 500 iterations using Monte Carlo simulation and 1-D closed-loop modeling.

6. Conclusions

GreenFire Energy, with California Energy Commission, Shell GameChanger Program, Electric Power Research Institute , and J-POWER funding, and with the strong support of the Coso Operating Company and the US Navy, has installed a demonstration downhole closed-loop heat exchanger into a well that has several megawatts of power production capability but contains NCG at concentrations that exceed the power plant gas extraction system. By installing the DBHX, the well was produced at a low flow rate and about 1 MW electrical power of steam equivalent was produced without NCGs. The parasitic power loss was about 13% of the production potential. Makeup water was required at about 30 kph, which for this particular well could be produced from the condensate leaving the well silencer. A geothermal power coproduction equation (in function of flows) was developed by statistic modeling; showing that optimized configuration expects to produce at least 1.2 MW by setting 12 kph of brine flow and 510 GPM of closed-loop flow; also, Monte Carlo simulation methodology that uses 1-D Thermodynamic closed-loop modeling equations forecast the geothermal power production

limits of this optimized configuration (1.18 MW – 1.24 MW) with 50% of confidence intervals. Both estimations show a good fitting, validate each other estimate's forecasting, and predict a 20% increase the maximum measured power from testing (1 MW). The primary goal of the project has been to demonstrate the effectiveness of a closed-loop heat exchanger under various operating conditions, and also to verify the modeling results. Indeed, the modeling results successfully predict about the same production rate of steam as was measured in the field.

7. Future Work

Additional testing and data analysis of results with water as the working fluid is ongoing. Initial testing with supercritical CO_2 as the working fluid has been completed and analysis of the data has begun. Measurements have been taken that will be used to determine closed-loop heat extraction capabilities when there is no well flow, which will simulate full-scale operation in hot, dry rock and enable fine tuning the modeling techniques and assumptions.

The sCO_2 testing uses a different arrangement, as the flow is completely closed loop and a surface heat exchanger is used to reject heat. This data will be analyzed and presented in a subsequent paper.

Of course, we plan to run more tests with water circulated to have a larger database of conditions to compare measured data to modeled data and also to predict statistical behavior with more accuracy.

Finally, since the modeling approach appears to accurately capture the heat transfer in the system, we will extend our modeling to consider other well and closed-loop configurations. For example, we intend to model performance with wells configured to include fins and rods to increase the rate of heat transfer, and model performance with alternative DBHX diameters and lengths to increase and optimize power production consistent with an appropriate cost-benefit analysis.

Acknowledgement

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