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# Comparison of Water, $sCO_2$, and Organic Hydrocarbons as Working Fluids for the GreenLoop System and ORC Unit

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## ABSTRACT

GreenFire Energy is involved in developing closed-loop geothermal technology and methods to efficiently and economically extract thermal energy from various geothermal and oil and gas resources. Initial analysis and projects often involve the retrofitting of existing underperforming/depleted geothermal and oil-and-gas wells with the longer term goal being the technology for use in new purpose drilled wells to create large projects in similar resources. Numerous process simulations have been carried out since the inception of the firm in 2014 using a variety of downbore working fluids in the closed-loop system. In particular, in 2019, at GreenFire Energy's test project at the Coso geothermal site in southern California, two such working fluids, namely water and supercritical carbon dioxide ($sCO_2$) were tested in GreenFire's GreenLoop™ down bore heat exchanger (DBHX) system installed in an existing geothermal well. These fluids were benign by nature, and therefore, any accidental thru-well leakage isn't considered an environmental issue. Over the years with significant advancements in manufacturing technologies, casing manufacturers have guaranteed their zero-leakage premium joint designs paving the way for the use of organic hydrocarbon working fluids (e.g., cyclopentane, isopentane or isobutane). To validate this, a test with water is planned for 2023, with support from the California Energy Commission at GreenFire Energy's proof of concept project at The Geysers geothermal site. By using organic fluids for the technology, it is possible to directly hook up an expansion machine (turbine or expander) straight from the wellhead outlet flange. Heat exchangers at the surface to transfer heat from the produced fluid to the ORC fluid will no longer be required resulting in substantial cost savings. Other advantages include the absence of scaling in, and other issues arising from the injection wells since injection wells are typically not required where the technology is used, long-term sustainability, and compatibility with non-flowing and sub-par producing wells. This paper compares water, $sCO_2$, and an organic fluid (n-pentane) as working fluids, baselined to one common well using the DBHX for heat extraction and thus electricity generation.

## 1. INTRODUCTION

GreenFire Energy Inc. (GFE) has been developing methods to efficiently and sustainably extract thermal energy from existing underperforming/depleted geothermal wells for a number of years (Amaya et al., 2020; Higgins et al., 2021). More recently, increased interest from the Oil and Gas industry to retrofit certain abandoned oil and gas wells has led GFE to develop closed-loop geothermal technology for the extraction of residual heat for such applications as well which is the purpose of a consortium of Oil and Gas companies led by Baker Hughes (Baker Hughes, 2022).

Over the years, intensive field testing of the GreenFire's GreenLoop® Down Bore Heat Exchanger (DBHX) has been performed in varying resource conditions to demonstrate its applicability and efficiency over a wide range of end-use applications (power production, direct use, industrial applications etc.). One of GFE's tailored solutions, the Steam and 2-Phase GreenLoop (S2PGL) is currently being implemented at The Geysers Known Geothermal Resource Area (KGRA) to aid with the sustainable extraction of heat, rather than mass from the resource. This helps in water and pressure conservation of the resource, thereby ensuring the long term sustainability of the resource as a whole (Scherer et al., 2022).

In 2019, GFE conducted its first scale demonstration in the Coso KGRA (Scherer et al., 2020). The project team installed and measured the performance of the DBHX in a Well 34-A20 that couldn't be produced through conventional hydrothermal technology due to the presence of high levels of Non-Condensable Gases (NCG's). Both water and supercritical carbon dioxide ($sCO_2$) were successfully tested as working fluids for the DBHX installed in the well. The project was clearly able to demonstrate the applicability of the DBHX to produce useful heat from idle or unproductive geothermal wells.

From an environmental safety standpoint, GFE's closed-loop geothermal approach has several eco-friendly characteristics (e.g., no waste streams, minimal visual and noise pollution etc.). In addition, with significant advancements in manufacturing technologies over the years, casing manufacturers are guaranteeing zero-leakage premium joint designs. This could potentially pave the way for the use of organic hydrocarbon working fluids (e.g., n-pentane, isopentane, isobutane, cyclopentane etc.) in the DBHX, thereby eliminating the need for a surface heat exchanger unit in addition to the DBHX.

Prior studies by Oldenburg et al. (2016), Fox et al. (2016), Scherer et al. (2020), Malek et al. (2021) and Beckers et al. (2022) have indicated the thermal hydraulic performance of closed-loop geothermal systems (co-axial, U-Loop, and multi-lateral approaches) using

$sCO_2$ and/or water as working fluids in a wide range of near wellbore/resource conditions (hot dry rock conditions to high enthalpy wells). Nalla et al. (2005) simulated the performance of a co-axial DBHX in a hot dry rock environment by varying the density and the specific heat capacity for a set of hypothetical working fluids. However, the model ignored variation in the thermophysical properties including viscosity variations along the DBHX and frictional losses through the casing and the tubing of the DBHX. Nalla et al. (2005) also simulated specific case examples of the DBHX in near surface magma conditions along with vapor-dominated environments such as the North west Geysers area (using water as a working fluid). However, the model didn't allow the formation fluids to flow in and out of the wellbore so that the primary mode of heat extraction was considered to be conduction even in these cases. Therefore, it is desirable to analyze the effects of multiple working fluids in a DBHX that is operated in convective environments.

In this paper, we have used the experimental data obtained from the DBHX testing at Coso, California (Well 34-A20) to simulate and compare the performance output of the DBHX operating with different working fluids. Studies have indicated the use of n-pentane in ORC units (Quoilin et al., 2013; Vankeirsbilck et al., 2011). Therefore, in this study, a comparative analysis study is performed using three DBHX working fluids, namely, water, $sCO_2$, and n-pentane. Results for other C5 hydrocarbon working fluids such as cyclopentane and isopentane are expected to be like n-pentane and hence have not been simulated in this paper.

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## 2. DESCRIPTION OF GREENLOOP SYSTEM

GreenFire's GreenLoop® system is a closed-loop geothermal technology that is tailored to sustainably extract heat from underutilized assets ranging from existing conventional geothermal to low permeability hot dry rock assets. The heat extracted through the GreenLoop system can be used for a variety of applications, including power generation, direct use (heating/cooling), and industrial applications to name a few. The closed-loop geothermal technology applied by GFE to specific resources typically involves the insertion of a tube-in-tube down bore heat exchanger (DBHX) into a well. The tube-in-tube system consists of an insulated tubing that is typically contained within an outer casing. The material of the outer casing can be designed based on the near-wellbore/resource conditions. When this technology is applied to existing geothermal wells, the system is called the Steam and 2-Phase GreenLoop (S2PGL). The S2PGL system can have several variations too which have been described in detail in prior research papers (Amaya et al., 2021; Scherer et al., 2022).

Depending on the application, a specific heat transfer working fluid is selected along with the flow direction within the DBHX (i.e. forward or reverse flow). Forward flow refers to injection of the working fluid through the center insulated tubing and production of the working fluid through the annular region between the outside of the insulated tubing and the outer casing of the DBHX. Reverse flow on the other hand refers to the injection of the working fluid through the annular region and production through the center insulated tubing. Prior studies analyzing the DBHX in hot dry rock resource environments have found reverse flows (considering water as a working fluid) to show marginally better thermal performance as compared to forward flow situations (Holmberg et al., 2016; Beckers et al., 2022). However, this might not always be the most optimal operating condition for all working fluids. For example, Fox and Higgins (2016) considers forward flow for the case of $sCO_2$ as a working fluid. This is because thermosiphon driven flows can be achieved more easily through forward flow operating conditions using $sCO_2$. In other words, better pressure control can be achieved in the forward flow situation with certain working fluids.

Besides the flow inside the DBHX, for fluids flowing outside of the DBHX (such as in the case of the S2PGL or in other instances where the GreenLoop technology is inserted in near-wellbore convective environments), the steam enters the wellbore and interacts with the relatively colder surface of the DBHX. This causes the steam to quickly condense to liquid with the latent heat of vaporization being extracted by the DBHX and captured in the working fluid. The liquid (by virtue of having higher density of steam) will flow downwards. Non-Condensable Gases (NCG's) (if any) can be vented at the surface if their concentrations are high. 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.

GFE's proprietary models can analyze, design and optimize the use of fluids and systems tailored to each specific resource and near-wellbore environment. The selection of a site with appropriate geothermal geological properties is important to optimize performance. For the S2PGL system there should be sufficient reservoir pressure, enthalpy, and permeability to provide good steam or two-phase fluid flow to the wellbore. Ideally, this occurs from a feed zone that is relatively shallow. The feed zone acts as the source of convective heat flux to the DBHX. Therefore, the length of the DBHX installed in a well is such that it is at or close to the feed zone depth. As encountered in many geothermal wells, there will typically be additional feed zone(s) or permeability near the bottom of the well which would aid in the reinjection of condensed fluids back into the reservoir. Greater detail on the modeling aspects pertaining to the S2PGL can be found in Higgins et al. (2021). Details with respect to the progress of S2PGL implementation in operational geothermal power plants can be found in Scherer et al. (2022).

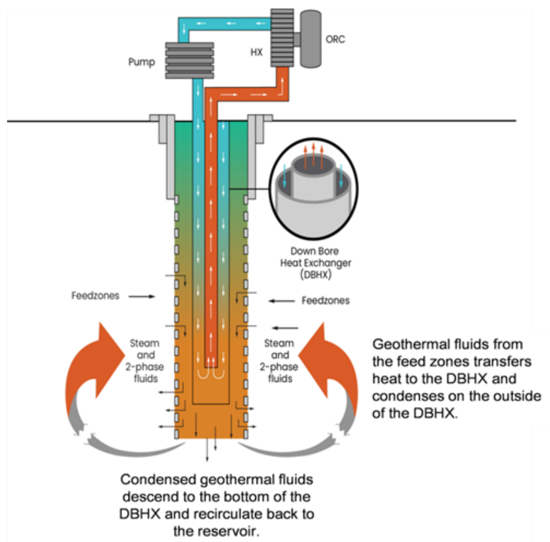


**Figure 1: The DBHX is inserted inside the well and, hung from the wellhead. The above figure shows the reverse flow operating condition within the DBHX (cold fluid enters through the annular region and hot fluids exit the well through the center insulated tubing, respectively). Geothermal fluid from the reservoir condenses and flows downwards in the well as depicted by the black arrows. The condensed fluids are recycled back into the reservoir to regain heat and produced in the feed zones again (Figure adapted from Scherer et al., 2022).**

## 3. SIMULATION METHODOLOGY USING THE COSO GREENLOOP TEST DATA

To calibrate GFE's model to simulate the performance of different working fluids in the DBHX, the Coso pilot testing data was used. The same configuration of the DBHX was chosen in this simulation study to match and calibrate GFE's DBHX model. The following subsections provide a recap of key technical aspects of the pilot test along with details on the DBHX model calibration for simulation purposes.

### 3.1 Experimental process flow description for water and S$CO_2$ as working fluids within the DBHX

The DBHX pilot testing project in Well 34-A20 at Coso employed both water and s$CO_2$ as downbore working fluids. The insulated tubing for the DBHX was chosen to be vacuum insulated (VIT) with a specification of 3.5 inches and 4.5 inches (inner and outer diameters, respectively). The outer casing was 7 inches. It is important to note that due to budgetary constraints, the DBHX was only inserted to a depth of around 330 m. The high permeability zone or the feed zone for the well was located at the end of the casing shoe at about 736 m MD. Due to the relatively short length of the DBHX and the high NCG content (around 25% by weight of the produced flow), the well was allowed to coproduce brine in the annulus between the outer casing of the DBHX and the existing well casing.

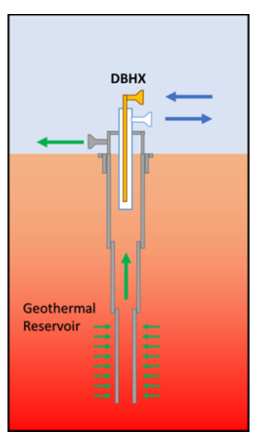


**Figure 2: Schematic showing the DBHX inserted in the Well 34A-20 at Coso. The blue arrows indicate the flow of s$CO_2$ within the DBHX (For water as the working fluid within the DBHX, the flow directions were reversed) and the green arrows indicate the flow of geothermal brine to the surface around the DBHX (Figure adapted from Scherer et al., 2020).**

The DBHX was operated in reverse and forward flow with water and $sCO_2$, respectively. The test with water was operated as a semi-closed loop system since a cooling system was not integrated with the outlet stream from the DBHX. Water was continuously supplied to the DBHX at a temperature of about 82 °C. However, the test with $sCO_2$ involved a heat exchanger (cooling unit) that made the DBHX process loop entirely closed.

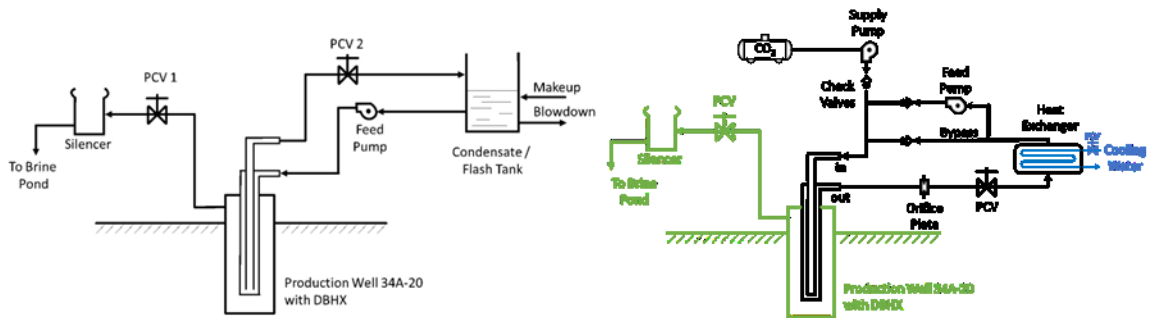


**Figure 3: The DBHX process flow diagram for water (left) and $sCO_2$ (right) as working fluids within the DBHX (Figures adapted from Amaya et al., 2020 and Scherer et al., 2020).**

### 3.2 DBHX model calibration with experimental conditions at Coso using water as a working fluid

Six different DBHX operating conditions were tested at Coso (tests T1 to T6) using water as the working fluid (Scherer et al., 2020). GFE's numerical model was calibrated by using experimentally obtained DBHX parameters (such as inlet/outlet temperature, pressure, flow etc.) and the flowing profile of the Well 34-A20.

Scherer et al. (2020) showed that the optimal steady state DBHX electric power extraction from the well was about 1.2 MWe (using the existing steam flash turbine system) considering a DBHX flow of about 23.2 kg/s. This corresponds to over 12 MWth in terms of heat extraction from the well. However, it is important to note that unlike conventional geothermal systems where well control is established only through the wellhead valve, the operating conditions of the DBHX can be controlled in a much more efficient fashion since conditions such as temperature, pressure and flow can be entirely controlled and modeled within the DBHX. Therefore, it is possible to operate the DBHX in a wide range of flow conditions (at flow rates that are either lower or higher than the optimal of 23.2 kg/s) as shown in Figure 4.

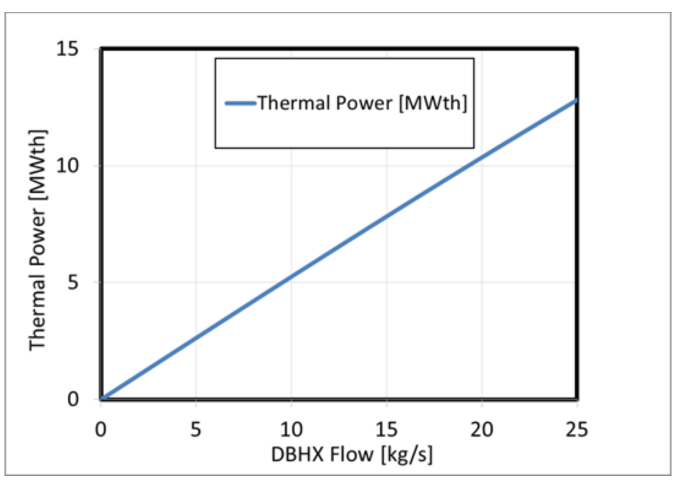


**Figure 4: Simulated plot for DBHX Flow as a function of Thermal Power extracted for the Coso Well 34-A20 using water as the working fluid for heat transfer.**

To compare the performance of 3 different working fluids namely water, $sCO_2$ and n-pentane in the DBHX system, a uniform long term or steady thermal power extraction of 5 MWth from the reservoir was considered for each of the working fluids simulated so as to be representative to certain low enthalpy geothermal and oil and gas wells. Besides, for consistency, forward flow is assumed in all simulation cases (since better pressure and flow control can be obtained when using forward flow with $sCO_2$ and n-pentane as working fluids).

## 4. DBHX PROCESS SIMULATION FOR WATER, $SCO_2$ AND N-PENTANE USING CALIBRATED THERMAL POWER

For the case of water as the working fluid, the mass flow rate of water required in the DBHX for a thermal extraction of 5 MWth can be obtained through extrapolation of Figure 4 to be about 9.5 kg/s (such a flow can be sustained in the DBHX through the use of a surface pump that can handle the working fluid). In other words, a DBHX water flow of 9.5 kg/s will result in a thermal extraction of 5 MWth.

To convert the heat extracted from water in the DBHX to useful work, it is essential that the DBHX is coupled with a power producing unit on the surface such as a steam flash unit or an ORC unit. Here, the process simulation considers the DBHX to be coupled with an ORC power producing unit that uses n-butane as a working fluid. Therefore, when water is used a working fluid, it is required that two flow loops be established i.e. primary and secondary loop. The primary flow loop consists of the DBHX pump and the DBHX. The secondary flow loop consists of the entire ORC cycle which includes a surface heat exchanger, expander, ORC pump and a cooling system. The cooling system can be water or air cooled. In this study a water cooling system is chosen and analyzed. The PFD for the entire system is shown in Figure 5.

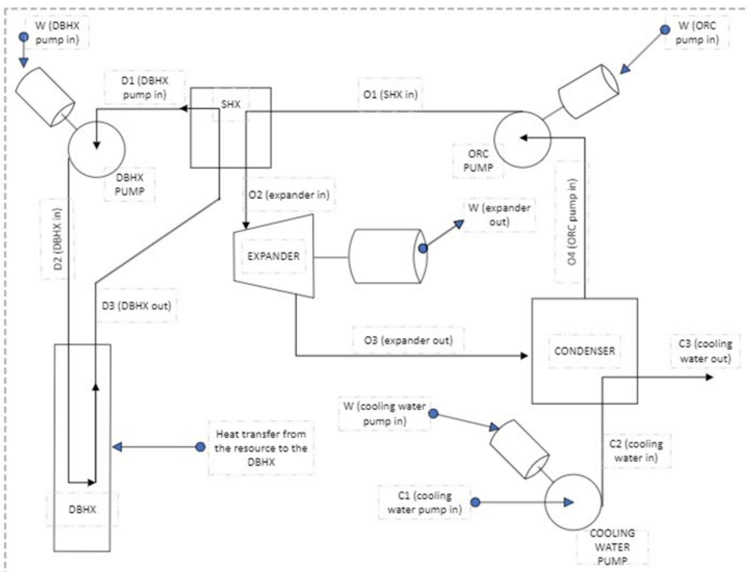


**Figure 5: Process flow diagram (PFD) of the GreenLoop system coupled to an ORC cycle at the surface. The GreenLoop system consists of the DBHX pump and the DBHX. The ORC cycle consists of the ORC pump, a surface heat exchanger, cooling system, and an expander for power production.**

The results from the DBHX wellbore simulation for a flow rate of about 9.5 kg/s have been detailed in Figure 6. The profile of pressure as a function of DBHX depth indicates that the pressure increases as the fluid flows through the VIT and decreases as the fluid flows up the annulus between the DBHX casing and the VIT.

This trend is observed primarily due to the hydrostatic pressure gradient which increases and decreases as the fluids flows down and up the DBHX, respectively. The differential pressure between the inlet and the outlet of the DBHX is primarily caused due to frictional pressure losses through the VIT and the annulus. Acceleration pressure losses are minimal in this simulation since there is no phase change. The temperature of the fluid remains fairly a constant as the fluid flows through the VIT with minimal increase in temperature due to the high insulating capability or low thermal conductivity of the VIT. However, as the fluid is exposed to higher temperatures at the bottom of the DBHX, there is an exponential increase in the fluid temperature as it flows up through the annulus leading to lower density and higher fluid enthalpy.

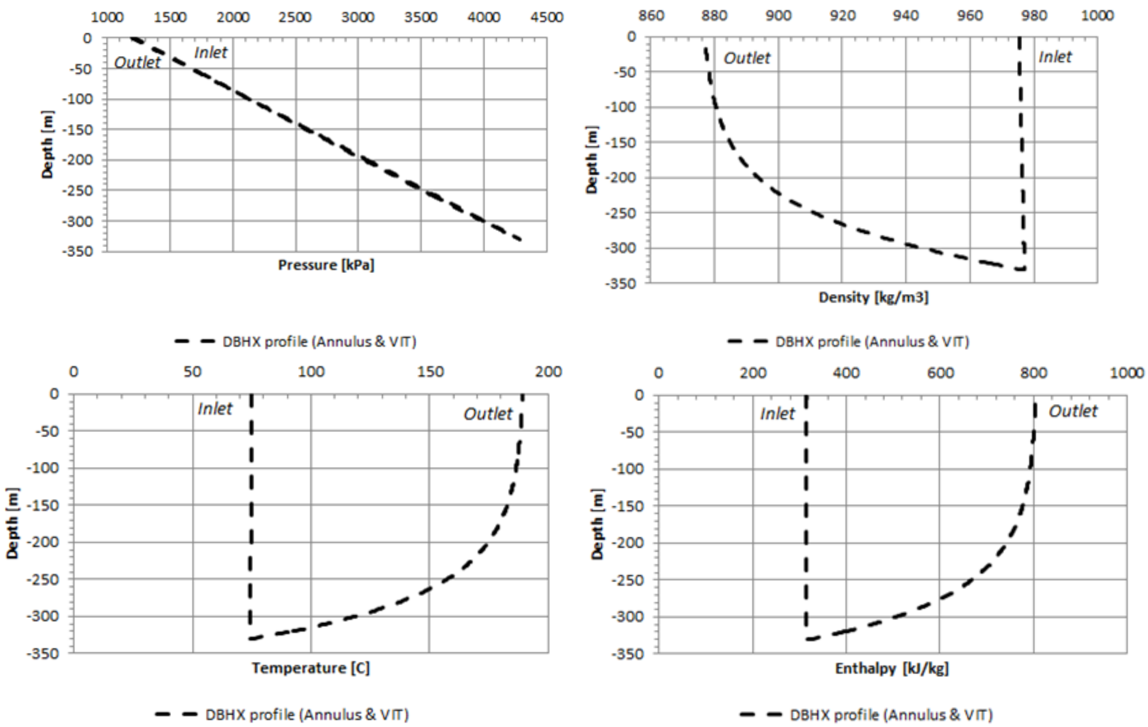


**Figure 6: Near-steady state profiles of pressure, temperature, density and enthalpy as a function of DBHX depth right from the inlet of the fluid through the VIT to the exit of the fluid through the annulus between the VIT and the outer DBHX casing. The wellbore simulation was performed for a mass flow rate of 9.5 kg/s of water within the DBHX which corresponds to a thermal power extraction of 5 MWth from the DBHX.**

The simulation results for the ORC cycle using n-butane have also been detailed below in Figure 7. The various points indicated on the plots refer to the streams in the ORC cycle. O1 refers to the surface heat exchanger (SHX) inlet stream, O2 refers to the surface heat exchanger outlet or the ORC expander inlet stream, O3 refers to the ORC expander outlet stream and O4 refers to the ORC pump inlet stream (streams can be pictorially seen in Figure 5). Through the entropy versus enthalpy and entropy versus temperature plots it can be observed that the heat gained by n-butane is higher than the critical point on its saturation dome. Therefore, the ORC system operates as a supercritical cycle.

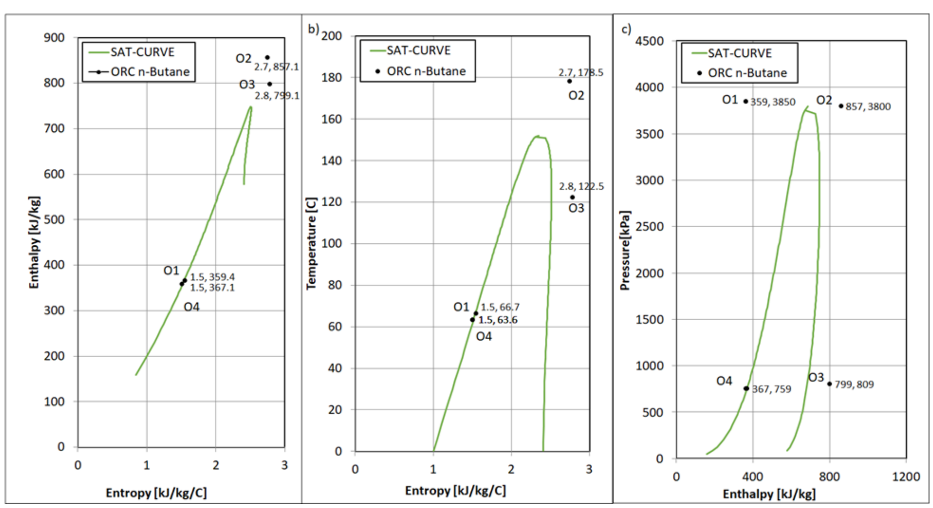


**Figure 7: Simulated thermodynamic profiles of entropy versus enthalpy (S-H), entropy versus temperature, enthalpy versus pressure for the surface ORC cycle using n-butane as the working fluid. The points O1, O2, O3, and O4 indicate the SHX inlet, expander inlet, expander outlet and the ORC pump inlet streams, respectively.**

A similar analysis was done for both $sCO_2$ and n-pentane as working fluids within the DBHX. It is important to note that in these cases, a secondary flow loop is not required since the need for a surface heat exchanger is eliminated. The entire PFD for the system is shown below in Figure 8.

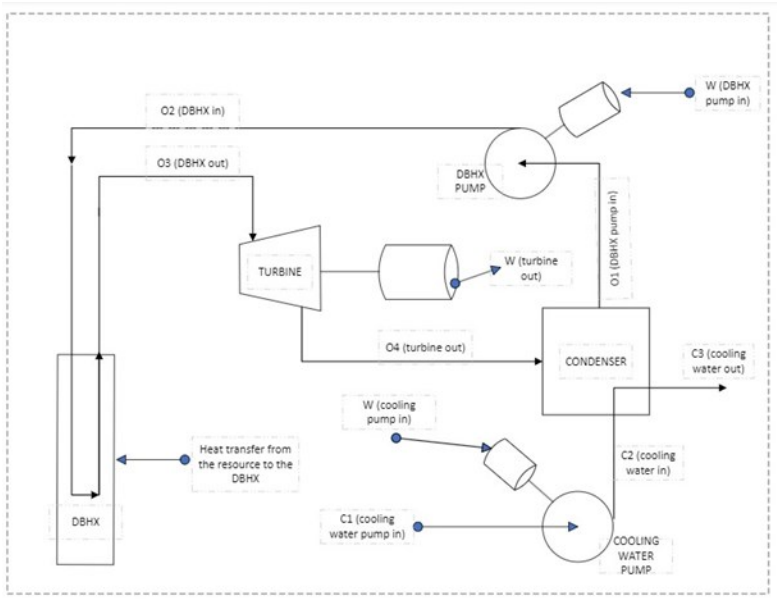


**Figure 8: Process Flow Diagram (PFD) of the GreenLoop system coupled to a turbine and water cooling system at the surface. The working fluid i.e. $sCO_2$ or n-pentane is pumped through the DBHX using the DBHX pump. The fluid is allowed to change phase within the DBHX and therefore the outlet stream from the DBHX is directly sent to the turbine for power production.**

The results from the DBHX wellbore simulation for a $sCO_2$ mass flow rate corresponding to a 5 MWth heat extraction have been detailed below in Figure 9. It is important to note that the mass flow rate of $sCO_2$ required is almost twice that of water for the same thermal heat extraction due to the lower heat capacity of $CO_2$ as compared to water. The overall trends for pressure, temperature, density, and enthalpy as a function of the DBHX depth for $sCO_2$ are quite similar to that of water. However, it can be observed that the pressure drop in the system is higher than that of water due to the higher flow rates. $CO_2$ is maintained in its supercritical state throughout the DBHX and thermal expansion occurs as the fluid travels up the annulus after exiting the VIT

Besides, the simulation results for the $sCO_2$ power cycle have also been detailed below in Figure 10 in which O1 refers to the DBHX pump inlet stream, O2 refers to the DBHX inlet stream, O3 refers to the DBHX outlet stream or the $sCO_2$ turbine inlet stream, and O4 refers to the turbine outlet stream. Through the entropy versus enthalpy and entropy versus temperature plots it can be observed that the thermodynamic states of $sCO_2$ in all the points are above the saturation dome proving the supercritical operating condition.

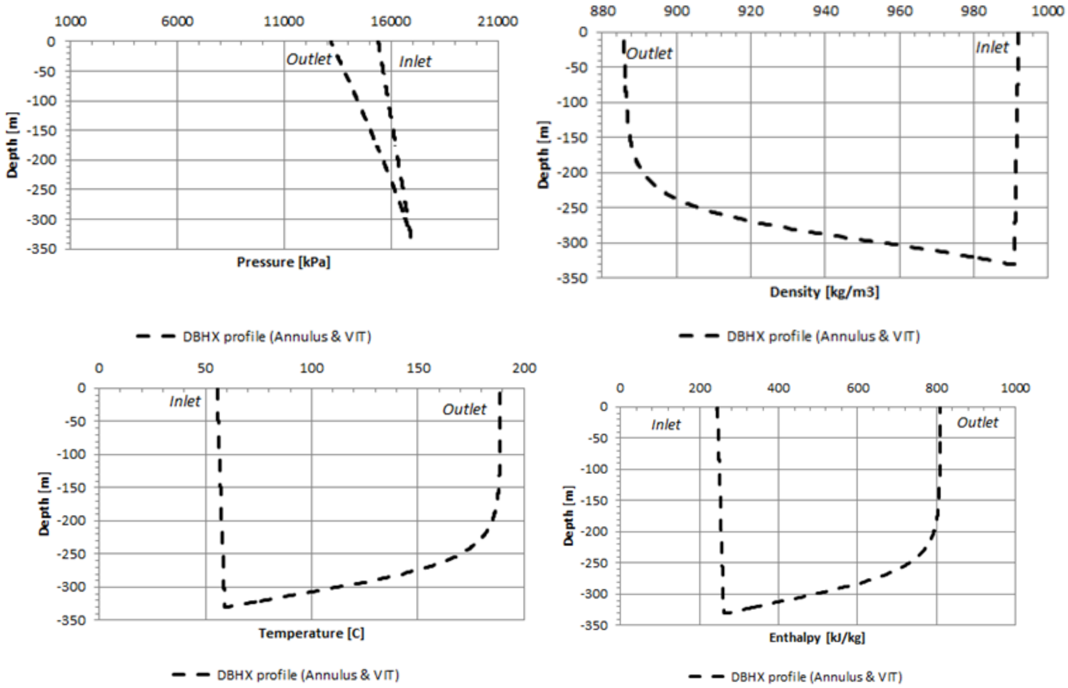


**Figure 9: Near-steady state profiles of pressure, temperature, density and enthalpy as a function of DBHX depth right from the inlet of the fluid through the VIT to the exit of the fluid through the annulus between the VIT and the outer DBHX casing. The wellbore simulation performed corresponds to a thermal power extraction of 5 MWth from the DBHX using $sCO_2$.**

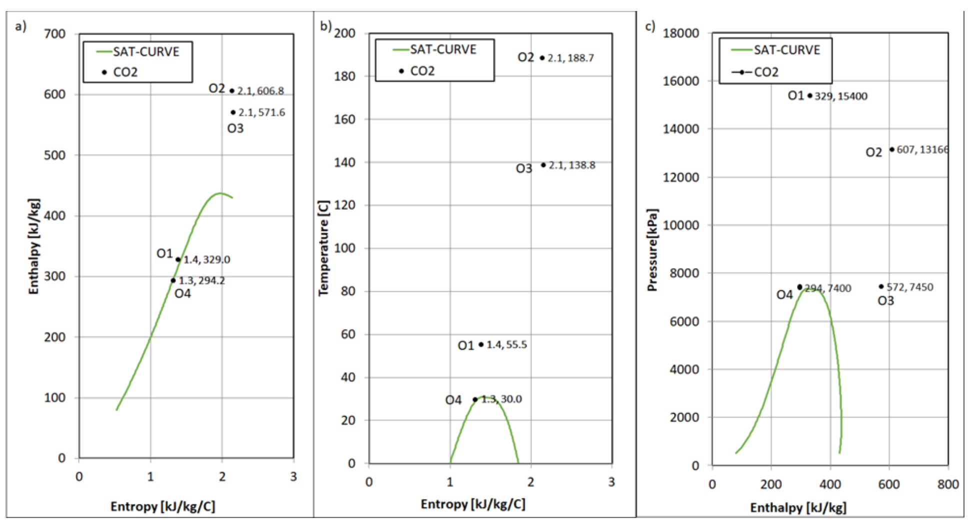


**Figure 10: Simulated thermodynamic profiles of entropy versus enthalpy (S-H), entropy versus temperature, enthalpy versus pressure for the $sCO_2$ power cycle. The points O1, O2, O3, O4 indicate the DBHX pump inlet, DBHX inlet, DBHX outlet, and turbine outlet streams, respectively.**

Similarly for n-pentane as a working fluid in the DBHX, the results from the DBHX wellbore simulation for a mass flow rate corresponding to a 5 MWth heat extraction have been detailed below in Figure 11 (the mass flow rate needed for n-pentane for the same thermal extraction was the least among the working fluids simulated in this study).

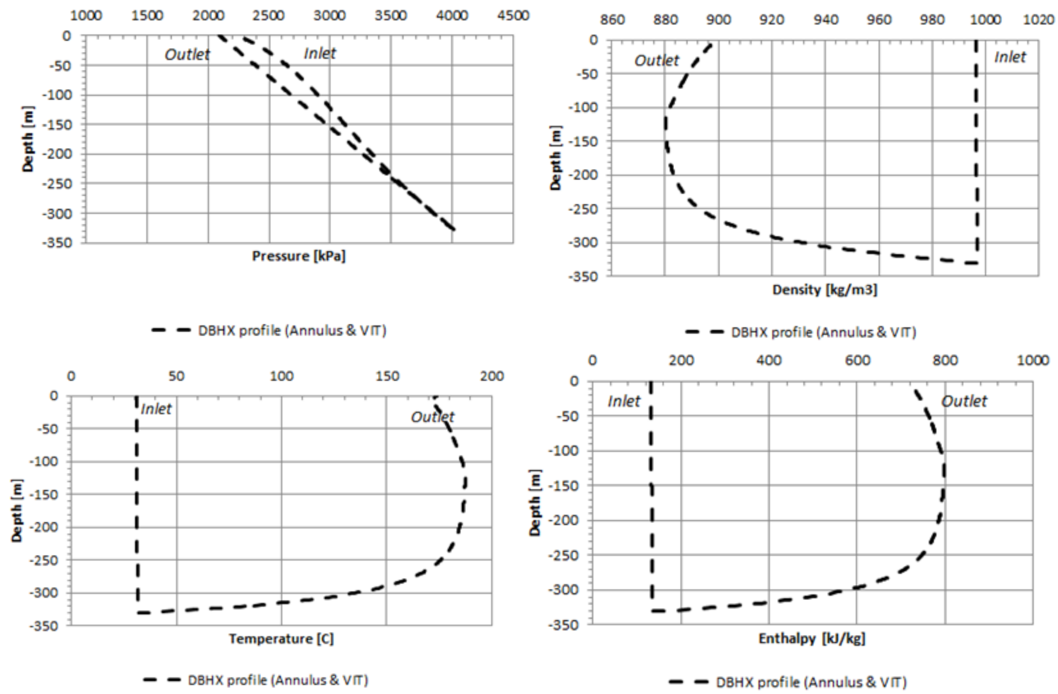


**Figure 11: Near-steady state profiles of pressure, temperature, density and enthalpy as a function of DBHX depth right from the inlet of the fluid through the VIT to the exit of the fluid through the annulus between the VIT and the outer DBHX casing. The wellbore simulation was performed for a mass flow rate of n-pentane within the DBHX which corresponds to a thermal power extraction of 5 MWth from the DBHX**

The simulation results for the n-pentane power cycle have been detailed in Figure 12. O1 refers to the DBHX pump inlet stream, O2 refers to the DBHX inlet stream, O3 refers to the DBHX outlet stream or the n-pentane expander/turbine inlet stream, and O4 refers to the expander/turbine outlet stream. Through the entropy versus enthalpy and entropy versus temperature plots it can be observed that the heat gained by n-pentane is well within its critical point. Therefore, the system operates as a sub critical cycle.

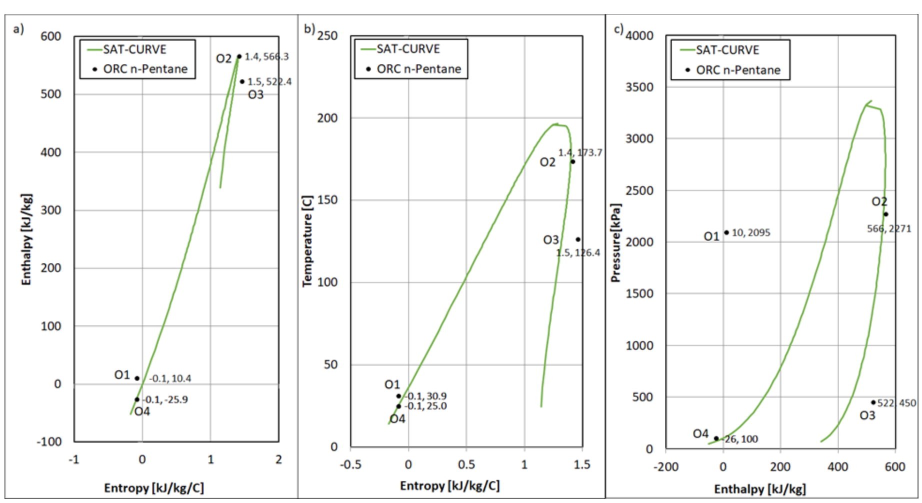


**Figure 12: Simulated thermodynamic profiles of entropy versus enthalpy (S-H), entropy versus temperature, enthalpy versus pressure for the n-pentane power cycle. The points O1, O2, O3, and O4 indicate the DBHX pump inlet, DBHX inlet, DBHX outlet, and turbine outlet streams, respectively.**

## 5. DISCUSSION

The key assumptions and results from the simulation scenarios run in this paper have been summarized below in Table 1. The surface pumps required in the system were assigned with appropriate efficiency factors. The various flow streams through units such as the surface heat exchanger and the cooling condenser were also assigned with appropriate industry standard pressure drops.

**Table 1: Process flow simulation summary for the different working fluids examined**

| Working Fluid Considered | Water + n-butane | $sCO_2$ | n-pentane |
|---|---|---|---|
| Heat Extraction | 5 MWth | 5 MWth | 5 MWth |
| Gross Power at the turbine/expander | 0.55 MWe | 0.70 MWe | 0.43 MWe |
| Parasitic loads from DBHX pump, water cooling pump, and/or ORC pump | 0.10 MWe | 0.40 MWe | 0.03 MWe |
| Net Power Produced | 0.45 MWe | 0.30 MWe | 0.40 MWe |

From the process system simulation for the three working fluids, the following aspects can be inferred for each of the working fluids as enumerated through the bullet points below.

- Using water as a working fluid resulted in no phase change within the DBHX unlike the simulations with $sCO_2$ and n-pentane. Therefore, from a control/stability standpoint, water shows superior characteristics since better control of velocity and pressure can be obtained
- Water and $sCO_2$ have the advantage of being benign fluids which are not flammable/combustible unlike organic hydrocarbon fluids such as n-pentane. Therefore, minor leaks (if any) in the subsurface system (through the joints of the DBHX) may not have adverse effects on the integrity of the system as a whole.
- When water is used as a downbore working fluid, it is possible to operate the system in a semi-closed loop manner with a steam flash unit (similar to the Coso pilot study analysis) as described in Section 3.1 of this paper. This has the advantage of a lower and more optimal pumping requirement, thereby improving the net power extracted at the turbine.
- When the thermal heat extraction requirements from the subsurface are low such as in the case of low enthalpy geothermal systems, depleted oil and gas well retrofit opportunities, and in certain hot dry rock environments where there is minimal permeability in the formation, the option of using $sCO_2$ as a working fluid can lead to increased efficiencies since the parasitic loads can be minimal and the fluid at low flow rates can flow through thermosiphon mechanisms.
- Significant research and development efforts are currently being put into the commercial scale development for $CO_2$ expanders due to the high efficiency, small equipment size and superior economics (Weiland et al., 2019). Besides, $CO_2$ is a cheap working fluid unlike organic hydrocarbons. All these factors in turn could lead to superior techno-economic performance of the DBHX with $sCO_2$ as a working fluid.
- Using $sCO_2$ as a working fluid can also help in decarbonization goals broadly and also aid in obtaining economic incentives (which can include tax incentives).
- Leak-free casing designs can accelerate the use of organic hydrocarbon working fluids in the DBHX leading to increased system efficiencies.
- Use of organic hydrocarbon working fluids in the DBHX to extract power from depleted oil and gas can particularly be beneficial since separate environmental permits might not be needed to project execution.
- Presently, out of the three simulations performed. The scenario with water + n-butane had the highest net power, followed by n-pentane and $sCO_2$. However, it is important to note that the scenario with water and n-butane requires an additional surface heat exchanger leading to increased capital and maintenance costs unlike the scenario with $sCO_2$ and n-pentane. The surface footprint also increases with the addition of extra surface equipment. Therefore, from a techno-economic standpoint, n-pentane is preferable.

## 6. CONCLUSIONS

Water, $sCO_2$ and n-pentane were analyzed in terms of their effectiveness as downbore working fluids in GreenFire's GreenLoop® down bore heat exchanger system (DBHX). The DBHX model was calibrated using the data obtained from a real-world pilot project where the DBHX was installed in Well 34-A20 at the Coso geothermal site in the year 2019. For the purpose of the wellbore simulation, a steady state heat extraction of 5 MWth from the DBHX was uniformly considered for the three working fluids. For the case of $sCO_2$ and n-pentane, the DBHX was directly coupled to a turbine/expander unit for power production; however, for the case of water, the DBHX was coupled to a surface ORC system that uses n-butane as the working fluid. Water cooling systems were considered for all the simulations in this study, although, it is to be noted that the GreenLoop system can be coupled with air cooling systems too.

Using $sCO_2$ as a working fluid proved to be advantageous for low enthalpy systems, retrofitting depleted oil and gas wells, and certain hot dry rock resources with minimal or no near-wellbore formation permeability. For the simulations run on this paper, water coupled with the n-butane ORC showed the highest net power. However, from an economic standpoint, an additional surface heat exchanger would be needed in this system leading to increased capital expenditures for the system. Besides, the additional heat exchanger can increase the overall surface footprint of the system. The simulation with n-pentane therefore proved to be most efficient in terms of both high level techno-economics as well as surface footprint. With advancements in $sCO_2$ expander technologies, techno-economically efficient and modular expanders can be created, thereby aiding in $sCO_2$ being a very favorable working fluid for future use in the DBHX. In addition, $CO_2$ can be sourced at very low costs as compared to other organic hydrocarbon working fluids and can also aid in decarbonization goals on a broader scale.

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