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Heat Transfer Modelling of an Unconventional, Closed-Loop Geothermal Well

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ABSTRACT

With approximately 13 GW installed capacity worldwide in 2017, the geothermal energy sector represents less than 1% of the total renewable energy mix. Although the Enhanced Geothermal System (EGS) concept faces technical and economic validation challenges and suffers from public acceptance issues, such system is considered to have the capability to unlock the significant deep geothermal potential worldwide. The development of unconventional deep well designs can help to improve the efficiency and reliability of EGS systems. An integrated reservoir-wellbore approach to model alternative EGS well designs is key to assess their long-term hydraulic and thermal performance, particularly in unconventional geological settings. A coupled wellbore-reservoir simulator, T2WELL/EOS1, is used to compare the estimated energy recovery with experimental results available in the public domain from a downhole coaxial heat exchanger (DCHE) installed in Hawaii, where a temperature of 358°C has been measured at a depth of 1962 m. Numerical results are also compared with analytical-based results from the literature, showing good agreement and demonstrating that the heat recovery from deep borehole heat exchangers can be accurately simulated.

Thermal performance and economic viability of a hypothetical DCHE with conducting fillers in high thermal gradient areas are also discussed, based on the results from the Hawaii case study. The findings provide guidance to assess the operating range of closed-loop single-well EGS designs in future studies.

1. INTRODUCTION

In the global energy mix, geothermal energy represents a slow growing activity with more than 13 GW installed capacity worldwide (IRENA 2019) but is still underrepresented compared to other renewable resources (1 %). By lowering costs and bypassing the specific site limitations in conventional geothermal systems, the Enhanced Geothermal Systems (EGS) (Tester et al., 1979) can theoretically be a solution to access more widely geothermal energy to produce electricity. Despite having showed progress in few testing sites to create a connected fractured reservoir (Lu, 2018), EGS faces issues regarding induced seismicity (Grigoli et al., 2018). The EGS single closed-well concept offers an alternative solution by circulating a working fluid in a closed wellbore or by connecting the wellbore to a fracture or geothermal fluids (Wang et al., 2010; Feng et al., 2015). However, the latter is still subject to limitations as it involves hydraulic fracturing in the wellbore surroundings.

Primarily developed for heating/cooling purposes (Lund, 2015), closed geothermal wells such as Deep Borehole/Coaxial Heat Exchangers (DBHE/DCHE) can recover geothermal heat without connectivity issues with the reservoir. The working fluid only circulates in the well through an annular space or through different systems such as U-tubes or parallels DBHEs (Song et al., 2017), without geofluid exchange.

Various geometries or working fluids (water, CO_2, isobutene.) have been investigated numerically, see Alimonti et al. (2018), for instance). The overall capacity of closed-wells is limited by the low heat surface exchange between the heat source and the working fluid, which renders those systems more efficient for producing heat rather than electricity, even in the case of high geothermal gradient (Renaud et al., 2019). Morita et al. (1992) have experimented a DCHE at the depth of 876 m in Hawaii and measured a maximum output thermal power of 373 kW and 76 kW after 7 days.

Alimonti et al. (2018) highlighted the existing methods to model single well systems, notably 1D numerical (Wang et al., 2010;, Pan & Oldenburg, 2014), or multidimensional through Computational Fluid Dynamics tools (CFD) (Noorollahi et al., 2015; Renaud et al., 2019). Closed-wellbore models have been generally coupled with a reservoir model to account for the heat exchange and fluid flow in the surroundings porous or fractured rocks.

Falcone et al. (2018) identified different well designs that could increase the heat transfer rate of DBHEs or DCHEs. Figure 1 (left) describes the concept from Hara (2011) for which graphite is implemented between the external casing and rock around a single well. Buchi (1990) has patented a concept for the injection of high conductive materials, such as graphite (500-140 W/m.K), into the bottom hole surroundings to create an enhanced conductive area (see Fig. 1 Right). Despite requiring injection processes in Buchi's patent, those innovations would empower DBHEs. If the heat transfer rate is sufficient, the two patents could recover vapour after a vaporization process around the bottom hole. Note that the use of a downhole choke or boiler could facilitate the phase change process by decreasing the pressure, as proposed by Wang et al. (2010) and Heller et al. (2014).

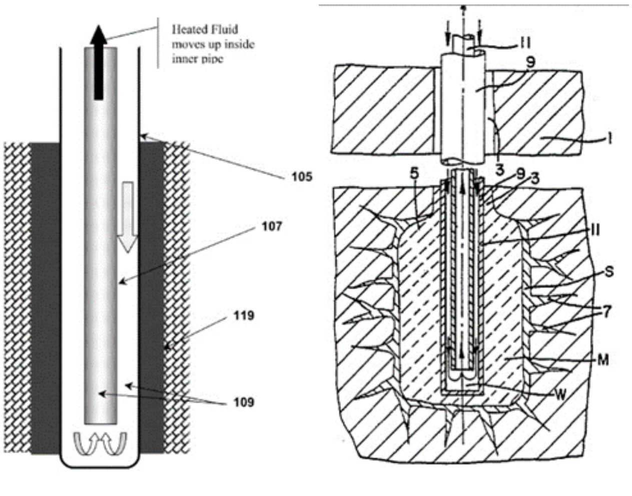


Figure 1: (Left) US Patent from Hara (2011) describing the possibility to implement high conductive filler of graphite between the external casing 105 and the cement or surrounding rocks 119 in a DCHE. (Right) US Patent from Buchi (1990) of a DCHE describing the injection of a high conductive material M in the near bottom hole.

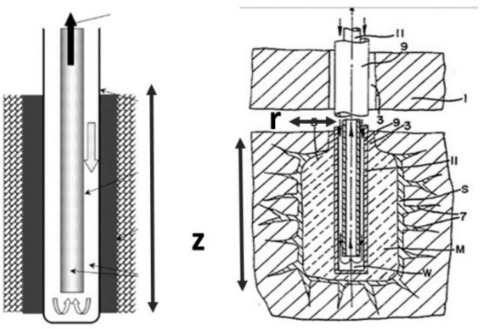
This study numerically investigates the thermal recovery of enhanced DBHE/DCHEs designs with T2Well (Pan & Oldenburg, 2014). By comparing the T2Well results with experimental data and a simulated closed-loop model performed with FEFLOW 6.2 (Falcone et al., 2018), DCHEs have been analyzed into different geothermal gradient environments.

2. METHODS

T2Well, a non-isothermal, multiphase, and multi-component fluid flow integrated wellbore–reservoir (Pan & Oldenburg (2014)) has been considered in this work. T2Well models the reservoir-wellbore system as two related sub-domains with different physical laws. In the reservoir sub-domain, the phase velocity is obtained by directly using multiphase version of Darcy's law. However, in the wellbore sub-domain, the phase velocity is obtained by solving a one-dimensional momentum equation for a fluid mixture, where the Drift-Flux-Model is used to model the interfacial interactions between the gas and liquid. The code has been used previously for Macondo flow-rate estimation (Oldenburg et al., 2012), Aliso Canyon blowout and kill analysis (Pan et al.,2018), closed-loop U-shape geothermal well analysis (Oldenburg et al., 2016), and many others (Pan and Oldenburg, 2014). The connections between well and formation have been closed to fluid flow in our models in this study so that only the heat transfer between wellbore and surrounding formations is considered. However the fluid flow within either wellbore or formations is still modeled. The equation of state (EOS1) that describes pure water in liquid, vapor and two-phase equilibrium (Pruess at al., 2012) is used with T2Well in this study. The water properties have been calculated following the steam table provided by the International Formulation Committee (1967). Apart from the study in Section 3.3, the DBHE has been modelled as described by Morita et al. (1992), see Fig.3 Left.

Several rectangular numerical grids have been built for the different cases investigated assuming a radial symmetry (see Section 3). All parameters and boundary conditions have been described in the corresponding sections. For this work, the formation default porosity is 1% and the permeability is 10^{-15} m^2, the formation heat capacity is 870 J/kg.˚C and a thermal conductivity of 2.5 W/m.ºC has been considered. The density of rock has been modelled with a value of 2700 kg/m^3. Injection and surface temperature have been set constant. A fixed mass flow rate is applied to the outlet of the inner pipe.

Several geothermal gradients have been simulated by setting up the maximum temperature (limited to 350ºC in T2Well) at the bottom of the models (Fig.2 Right). The high conductive material has been set as graphite with a density value of 3050 kg/m^3, porosity of 1 %, and a permeability of 10^{-16} m^2. The graphite thermal conductivity is equal to 300.0 W/m.K with a heat capacity of 710 J/kg.˚C. The height (z) of graphite implemented or the radial (r) injection have been investigated, as described in Fig. 2 Left. The enthalpy calculation has been performed using the IAPWS-IF97 formulation (IAPWS, 2007). The total energy flow rate including the kinetic and gravity potential energy has been calculated by T2Well according to Pan et al. (2014).



Simulated case	DCHE depth (m)	Geothermal gradient (ºC/km) – bottom temperature depth (m)
1	1000	170 – 2000
2	1990	170 – 2000
3	1990	85 – 4000
4	3990	85 - 4000
5	3990	56 - 6000

Figure 2: (Left) Description of the vertical sensitivity (z) and radial (r) investigated in the study. (Right) Description of the simulated cases using a DCHE.

3. CLOSED-LOOP GEOTHERMAL WELL MODELING

3.1 Downhole Coaxial Heat Exchanger model

The experiment conducted by Morita et al. (1992) in Hawaii aimed at proving the concept of Downhole Coaxial Heat Exchanger (DCHE) (Fig. 3 Left) by plugging the HGP-A well at -876.5 m. This well measured a bottomhole temperature of 358°C (-1962 m). Water at 30°C was injected with a flow rate of 80 l/min (i.e. 1.33 kg/s) at a constant pressure of 1.5 kgf/cm^2 (i.e. 147102.1 Pa) into the coaxial BHE from the 22nd of February to the 1st of March 1991.

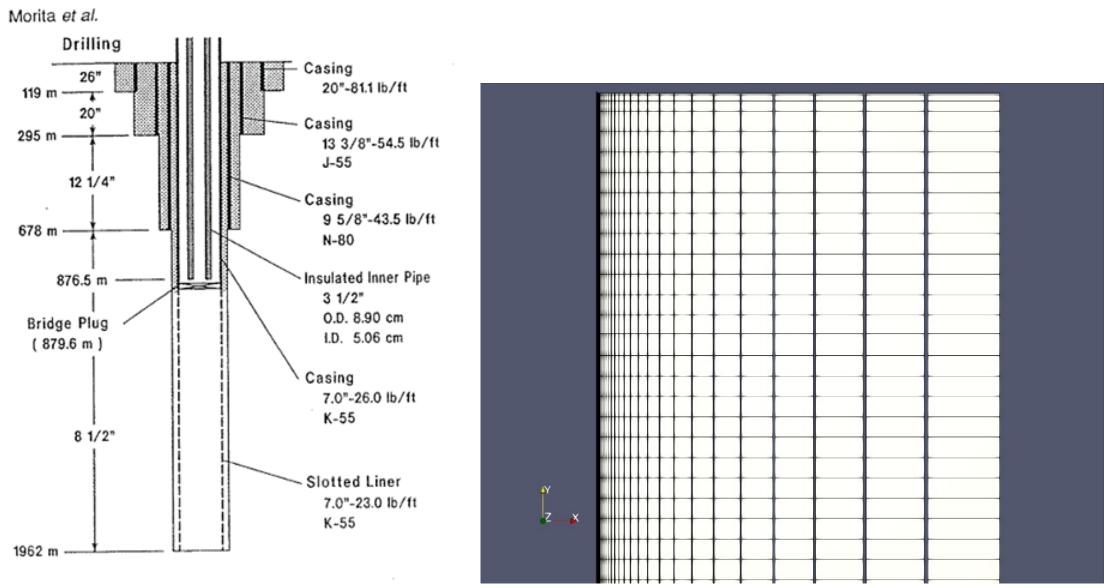


Figure 3: (Left) DCHE details experimented in Hawaii Morita et al. (1992). (Right) 2D slice of the mesh used with T2Well with 5 m horizontal and 500 m vertical.

After plugging it, a temperature of 110 °C was measured at the bottom of the DCHE (-876.5 m) before the injection. The formations around the DCHE were described as magmatic series, making the transition between surface and sea floor eruptions. The experimental installation measured the temperature and pressure at the end of a 28 m horizontal pipe in surface, thermally insulated. For the sake of simplicity, this horizontal part has not been accounted for in the T2Well model, but it has been anticipated that this simplification will produce a slight difference in the numerical results. Heat exchange has been only considered between the casing and wells cells. The casing and cement sections have been modelled according to the DCHE design. The model has been extended to 5 m in the radial direction (Fig 3 Right). Assuming a radial symmetry, the mesh is completed with a maximum cell height of 27.5 m. A logarithmic discretization scheme has been used to generate the mesh in the surroundings formations after the external casing. The model contains a total of 1310 cells reaching the maximum depth of 1931 m with a bottom temperature of 350°C.

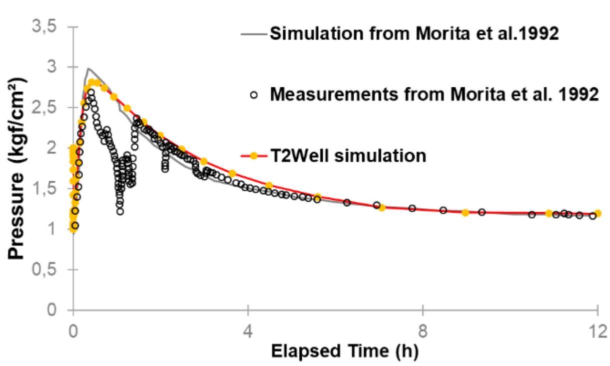
3.2 Modeling comparison with experimental data

Some assumptions have been made in the model. All formations have been set with a porosity of 0 % and a permeability of 0 m^2 in order to consider conductive heat transfer processes. Table 1 summarizes the parameters used in Morita et al. (1992) and in the study.

Table 1: Density and thermal properties of the materials used to simulate the experiments from Morita et al. (1992). The bold values are the values used by Morita et al. (1992).

Materials	Density (kg/m³)	Specific Heat (J/kg.K)	Thermal Conductivity (W/m.K)
Formation	3050 / **3050**	870 / **870**	1.6 / **1.6**
Cement	1830 / **3050**	1900 / **1900**	0.99 / **0.99**
Casing	7850 / **7850**	470 / **470**	46.1 / **46.1**
Inner Casing	7850 / **7850**	470 / **470**	0.06 / **0.06**

Fig.4 (Left) shows the pressure distribution calculated by T2Well, when considering a wall roughness height of 85 µm at the well. As can be seen, the model fails to capture the early drop of pressure taking place around 2 hours after the start. However, globally, the T2Well based numerical results show good agreement with both the numerical results from Morita et al., and their experimental data.



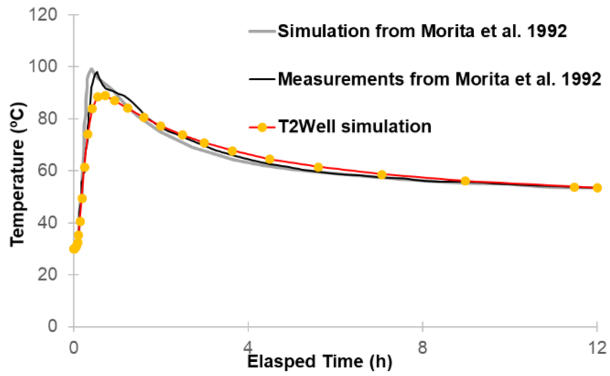


Figure 4: (Left) Pressure distribution calculated with T2Well, simulated and measured from Morita et al. (1992). (Right) Output temperature calculated with T2well, simulated and measured from Morita et al. (1992).

Regarding the temperature distribution shown in Fig 4 right, the T2Well simulated result displays a lower rise of temperature in the initial period when compared to the experimental curve. A more detailed model is required to match more accurately the data obtained by Morita et al. (1992). Nevertheless, T2Well shows good capabilities to reproduce the behavior of a DBHE in high geothermal gradient.

3.3 Modelling comparison with conductive fillers

T2Well has also used to compare the temperature production from a hypothetical DBHE with conductive fillers presented by Hara (2011) (see Fig. 1 Left). The deep geothermal system has been based on the KTB deep borehole project with a bottom BHE depth set at 7000 m. The geothermal gradient is 40 ºC/km. All parameters of the model have been described in Falcone et al. (2018), where FEFLOW 6.2 has been applied to simulate the single-phase flow of water with constant thermal properties using a 1D finite element approach. Graphite with a conductivity of 300 W/m.K has been set up between 4400 and 7200 m, i.e., between the borehole diameter (0.3175 m) and the inlet pipe (0.2445 m). Water has been injected in the annular region at 15 ºC with a flow rate of 604.8 m^3/day (i.e. 6.9937 kg/s). Whereas the authors have built a mesh containing 49420 elements, T2Well has been use with a mesh of 1030 cells with a radial extension up to 1000 m.

The transient temperature production comparison with T2Well and the temperature presented in Falcone et al. (2018) for a 10 years period is presented in Fig. 5. The temperature trend is similar for both cases. As the water thermal properties are pressure-temperature dependent in T2Well, the produced water temperature after 10 years is below 100ºC while the temperature from FEFLOW 6.2 is greater than 110ºC. Numerically, applying constant thermal properties seems to overestimate the thermal output compared to the result based on real water properties.

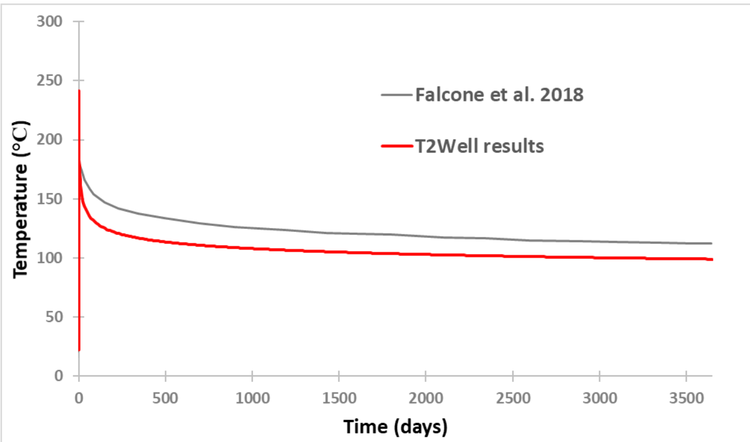


Figure 5: Temperature production simulated with T2Well compared to FEFLOW results (Falcone et al., 2018).

The following part of this study describes a sensitivity analysis of the implementation of high conductive materials in a DBHE/DCHE for different geothermal gradients and well depths.

4. RESULTS

The following results up to Section 4.4, are produced with Case 1 described in Table 1. All well parameters are identical to those used in Sections 3.1 and 3.2, with the HGP-A well described by Morita et al. (1992). The bottom of the inner pipe is 3.1 m above the bottom of the well. The theoretical environment is a rock with 10 % porosity, a permeability of 10^{-15} m^2 and a thermal conductivity value of 2.5 W/m.K.

4.1 Hara and Buchi Patent analysis

Fig. 6 presents the transient temperature obtained for 6 months for different water mass flow rates injected in the system. The vertical extension of graphite from the bottom hole (50-100-200 m) is considered in Fig.6 (Left). These results are plotted and compared with the cases where graphite is present on the whole length of the well (all length) and when no graphite is present (normal) for each mass flow rate injection (Fig 6. Left). The early high water temperature production rapidly reaches a slow decrease behaviour (see Section 3.3). The long-term temperature is as high as the mass flow injection is slow. The increase of graphite material along the wellbore increases the efficiency of the heat transfer for all mass flow rates studied, with an optimum obtained when considering the whole length. This effect is more apparent for low mass flow rates.

Fig. 6 (Right) shows results obtained on the Buchi's patent case for which the enhanced conductivity zone filled with graphite with porosity of 1% and a homogeneous permeability of $10^{-16}m^2$, varies vertically (z = 30-50-100m) from the bottom with a 50 cm radial extension (r = 50 cm). Similarly, the surface increase of the high conductive zone improves the heat recovery. Injecting graphite all along the well, following Hara's patent, demonstrates an improved heat recovery efficiency compared to the artificial injection of graphite in the rock around the bottom hole.

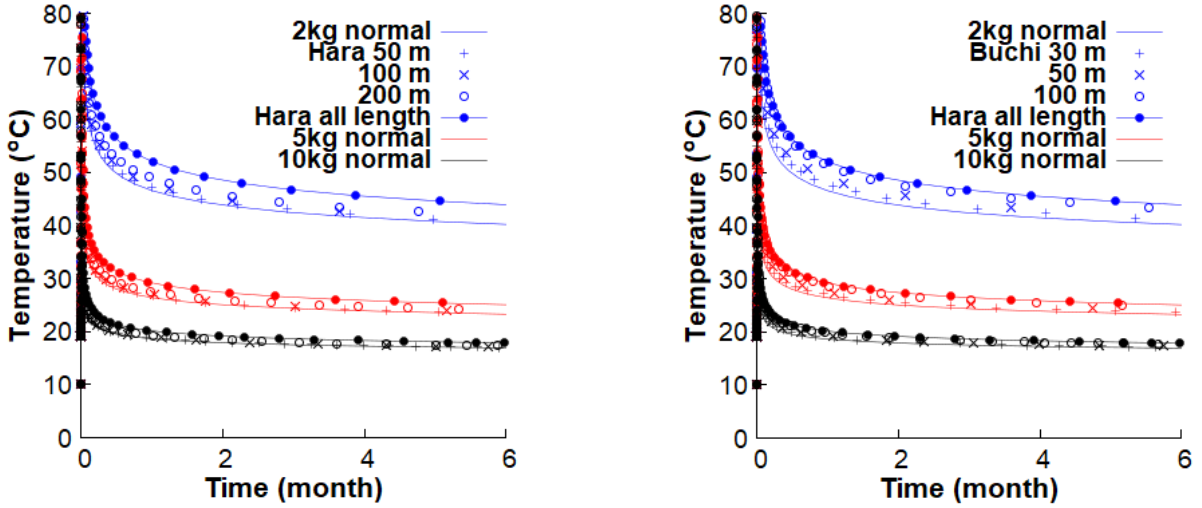
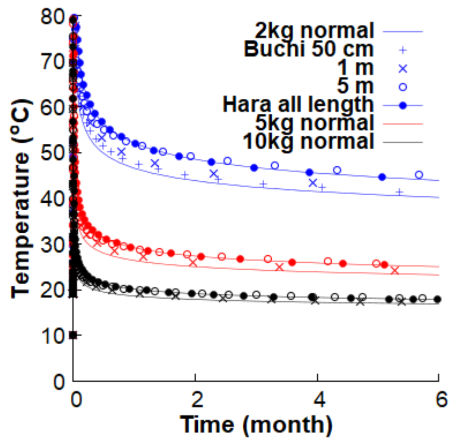


Figure 6: Produced water temperature during 6 months for Case 1 with different mass flow injections following the vertical length of graphite along the wellbore (z) (Left) and following the vertical length of graphite along the wellbore (z) (Right). Normal states the results for a DCHE without graphite on the wellbore.

The implementation of graphite for different radial distance (50 cm-1 m-5m) is shown in Fig.7 (Left) with a vertical length (z) of 30 m (see Fig.2 Left). The volume increase of conductive materials enhances the temperature production similarly as described in Fig.6. A 5 m radial extension of the enhanced conductive zone provides a similar efficiency than with the Hara patent on the whole length of the wellbore (Hara all length). Assuming no fluid losses during the injection of graphite along the well, the total volume needed to implement the different best scenarios (Hara all length and r = 5m, z= 30 m) is summarized in Fig. 7 (Right).



	R_out (m) / R_in (m) / z (m)/ case	Volume (m³)
Hara's patent (all length)	0.11119 / 0.0889 / 1000 / 1	14
	0.11119 / 0.0889 / 1990 / 2-3	27.86
	0.11119 / 0.0889 / 3990 /4-5	55.87
	0.11119 / 0.0889 / 5990 / 6	83.88
Buchi's patent (30 m vertical)	0.5 / 0.0889 / 30	22.8
	1 / 0.0889 / 30	93.45
	5 / 0.0889 / 30	2354.256

Figure 7: (Left) Produced water temperature during 6 months for the case 1 with different mass flow injection following the radial length of graphite along the wellbore (r) and z = 30. The simulated results are higher than 100°C but the vertical axis has been limited to 80°C to observe the long-term temperature difference between the cases. (Right) Volume of Graphite needed for different diameters and length in the Hara and Buchi's patent.

Regarding the efficiency similarity of both patents, as showed in Fig.7 (Left), the potential cost and technical feasibility of the solution drives the choice to Hara's patent for the longest wells (Cases 4-5-6 in Figure 2 Right) as injection methods would be needed in Buchi's case.

4.2 Early vapour production

The transient production of water from the DCHE shows temperatures greater than 100ºC. If the pressure at the outlet is around the water boiling point, a phase change process can occur at the surface. The vapour fraction at the outlet of the DCHE is shown in Fig.8. Following the mass flow rate injection, a variable vapour fraction appears at the surface of the DCHE during several hours. As soon as the produced temperature becomes too low, liquid becomes the only remaining phase. The appearance of vapour is interesting as it raises the power output, through the enthalpy of the vapour (see Section 4.4). Assuming a decrease of the outlet pressure to 1 bar in a surface facility, the vapour production in surface can be increased in time following the production temperature. Note that no vapour is observed at the bottom hole in the cases investigated. This means that the hydrostatic pressure overcomes the static temperature to prevent water from boiling.

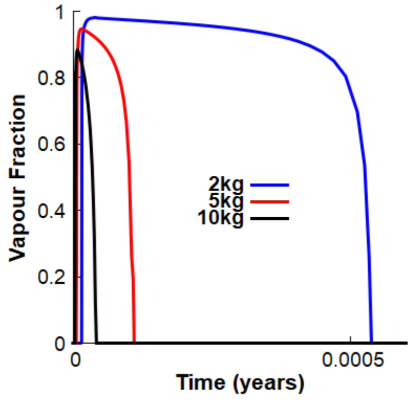


Figure 8: Vapour fraction in the early stage of the simulation following the mass flow rate injection for a duration of 0.0005 years (~4.3 hours) for Case 1.

4.3 Geothermal gradient and DCHE length sensitivity for the Hara's patents

All the cases presented earlier in Fig.2 Right are now simulated for 6 months with graphite present on the whole length of the wellbore (Hara all length). The enthalpy and energy flow rate are shown in Fig.9. The enthalpy increase present in several cases is due to the vapour produced from the DBHE after 6 months. The length of the well is pre-eminent to insure a high thermal recovery. The potential energy recovered from 0.37-2.9. MW after 6 months. A DBHE of 3990 m implemented in a geothermal gradient of 56 ºC/km gives similar thermal power than for setting up the well at 1990 m with a gradient of 170 ºC/km.

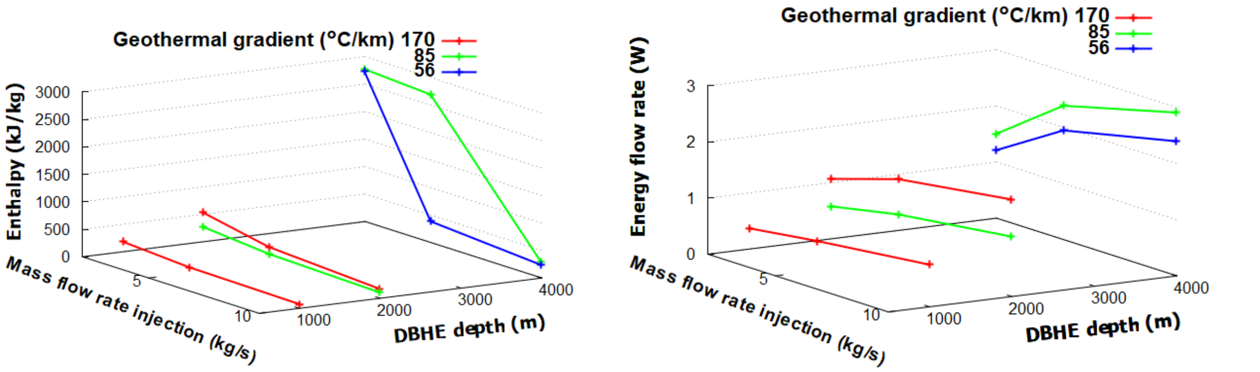


Figure 9: Enthalpy value (Left) and Energy flow rate (Right) at the surface of the inner pipe of the DCHE following the mass flow rate injection, the DCHE depth and geothermal gradient after 6 months.

The results presented in Fig.9 Right are compared to those obtained without graphite on a DBHE in Table 2, to highlight the percentage of increase of energy flow rate produced after 6 months of operation. The implementation of graphite enhances the thermal recovery in high geothermal gradient by more than 5 % in most cases (Cases 1, 2, 3 in Table 2). However, it decreases the energy flow rate for a mass flow rate of 2 kg/s in the Case 4 and 5. As they represent long DBHEs for a low mass flow rate, the higher thermal conductivity using graphite leads to a higher heat exchange during the beginning of the simulation. Thus, less energy is available after 6 months.

The heat transfer rate is high enough to provide a long-term production of hot water and/or a fraction of vapour. Producing electricity from a DBHE/DCHE is challenging but could be considered with vapour production at the surface (or the downhole) and setting-up a choke to decrease the local pressure and observing a phase change transition, as proposed by Wang et al. (2010). Other parameters such as underground flow, fracture connectivity around the well, diameter of the well or injection temperature could be considered in the future.

Table 2: Percentage of increase between the net thermal output using a DBHE base case and with Hara's patent on the whole length of the wellbore.

Cases - Mass flow rate	1	2	3	4	5
2kg/s	9.19 %	21.47 %	5.77 %	-1.89 %	-2.60 %
5kg/s	7.59 %	10.10 %	8.84 %	8.21 %	7.45 %
10kg/s	5.65 %	9.98 %	7.86 %	10.86 %	10.03 %

4. CONCLUSION

A heat transfer model of a DBHE has been created with T2Well, showing a good agreement with experimental data. The thermal performance of improved DBHE/DCBHEs in high geothermal gradient with high conductive graphite materials on the wellbore or in the bottom hole surroundings during a 6-month period has been studied, considering different mass flow rate injections with different high geothermal gradients. In terms of efficiency and technical issues, the Hara patent is the preferred option to improve the economics of the DBHE/DCHE system. The use of graphite placed along the wellbore can improve up to 21% the thermal recovery compared to a standard DBHE. From the cases investigated here, a maximum energy flow rate of 3 MW could be extracted after 6 months. T2Well can help investigating further unconventional geothermal wells and unlock the deep geothermal potential.

While EGC are facing technical and economics limitations, developing efficient single well DBHEs with innovative technology could bypass the current site specific locations dependency of geothermal energy, without hydraulic enhancement technics.

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