Engineered Geothermal Systems Using Advanced Well Technology

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Keywords

Dual perforation, multilateral doublet, enhanced geothermal systems, feasibility study

ABSTRACT

The feasibility of wellbore heat exchangers for power generation and/or direct applications has been analyzed and the research had shown that the conventional wellbore heat exchanger is not viable for electric power generation but could be used for direct heating applications. Variations in the methods and paths of fluid circulation to enhance the heat extraction using a single well are proposed and studied to determine its potential for thermal energy extraction and power generation. One such enhanced circulation is the dual perforation system, creating a hydraulic circulation system near the wellbore, in which the working fluid is allowed to circulate out from the top perforation interval, flows through the formation, thus establishing direct contact with the formation rock and in situ fluid, and drawn back into the well through the bottom perforation interval. Another advanced technique is the multilateral technology that is currently being used in the oil & gas industry. In a multilateral system, several lateral wellbores are connected to the main wellbore, thus creating a complex drainage architecture which significantly increases the heat transfer surface area. The analysis on the vertical well multilateral doublet approach suggested it to be promising for enhanced geothermal systems. An effluent fluid temperature of 60.4°C (increase of 33.4°C) and an ideal work extraction rate of 536 kW evaluated at the bottomhole reservoir conditions at 5 years was obtained with a circulation rate of 12.62 kg/s from a 60. m lateral well spacing in sedimentary bed using the best case vertical well multilateral doublet system. The dual perforation system and multilateral doublet in a horizontal well intuitively appears to be more promising for power generation than vertical well and wellbore heat exchanger since the significant parameter, the distance between the injection/extraction intervals, would become unconstrained and a larger in situ rock-working fluid contact volume would become possible.

Introduction

Engineered Geothermal Systems (EGS) are thought of as being either permeability-limited or fluid-limited such that the production of thermal energy from the reservoir becomes technically difficult and economically unviable. In such formations, wherein there is substantial thermal energy in place but is not readily available for production, several advanced techniques are being proposed to economically extract this energy.

In this paper, advanced well completion technologies for extracting this thermal energy will be studied using numerical investigations. The advanced well technologies under investigation include the forced hydraulic convection system through dual perforation intervals and the multilateral technology. Wellbore heat exchangers have been studied in the literature and it was concluded that they are not viable for electric power generation (Nalla et. al., 2004 a & b). The wellbore heat exchanger has the limitations of small fluid residence times, small heat transfer (formation-wellbore) contact area, the absence of contact between the working fluid and the in situ rock and slow heat transfer from formation to wellbore by thermal conduction.

Herrling *et al.* (1990) introduced the hydraulic circulation system for in situ remediation of contaminants within a "vacuum vaporizer well" (UVB). This UVB technique produces a vertical circulation flow in the area surrounding the well and this vertical velocity component yields a desired flow through the horizontal structure of native aquifer. They conducted numerical experiments to correlate the size of the sphere of influence and the capture zone of a well or well field with various parametric ratios. A similar approach was adopted for inducing a vertical circulation flow in the area surrounding the wellbore in geothermal reservoirs.

In the multilateral system, there exists a main wellbore to which several lateral wellbores are connected at the multilateral junction. The potential reservoir drainage area per wellbore is increased significantly by implementing a complex drainage architecture. The petroleum industry (Emerson, 2003; Zhang, 2004; Halliburton, 2004) has made significant progress in using unconventional well completion methodologies (expanding tubulars, multilateral technology, intelligent well controls) to significantly increase the hydrocarbon production capability of a well and cost effectively drain reservoirs. The geothermal industry (Baker Hughes, 2004) is also experimenting with multilateral well systems in producing geothermal reservoirs.

Relationships between the effluent fluid temperature and ideal work extraction rates with parameter variations in the dual perforation interval and multilateral well technology was investigated in this paper. Ideal work was calculated from the fluid enthalpy and entropy at production pressure and temperature, with rejection to ambient conditions of temperature of 27ºC and pressure of 1.0 atm. An ideal heat engine would be able to convert all of the ideal work extracted into electric energy. Though in reality there is an efficiency factor associated with the conversion, we decided to report the ideal work extraction rate, as this represents the theoretically maximum possible electric power generated and a means of measuring the viability of the process.

Advanced Well Technologies for Enhanced Geothermal Systems

Vertical Well Dual Perforation System

In a vertical well dual perforation system, a vertical well is drilled into the formation with two perforation intervals and isolation in the annulus between the two perforation intervals. The perforation interval is a portion of wellbore that has been prepared for facilitating production of fluids by creating channels between the reservoir formation and the wellbore (Schlumberger Oilfield Glossary, 2003). A schematic diagram of the vertical well dual perforation system is shown in Figure 1. In a conservative approach, the fluid temperature and ideal work extraction rate would be determined at the temperature and pressure conditions of production perforation interval. A source/sink term is used to represent the dual perforated intervals of the wellbore. This case is modeled in 2D Cartesian co-ordinate system. The reservoir domain extends to 30710. m in the x-direction, 20. m in the y-direction and 6100. m in the z-direction. The sedimentary bed is 150. m in thickness and extends from 4192. m to 4342. m and the rest of the formation is impermeable. The sedimentary bed had a horizontal permeability of 100 mD and a porosity of 10 %. The base case had a vertical to horizontal permeability aspect ratio of 0.1. Boundaries were far so as to cause no effect on the circulation process near the wellbore. Variable grid block size was adopted in the x-direction ranging from 20. m at the perforation intervals to 830. m at the reservoir boundary, 20. m in the y-direction and variable gridding in the z-direction ranging from 10. m at the perforated intervals to 76. m near the domain boundaries. The domain was discretized into 125 x 1 x 166 gridblocks. No-flow boundaries exist on the top and bottom sides of the model. A pressure boundary condition was given at the model edge with the pressure being specified at the initial reservoir pressure. A basal heat flux of 0.1 W/m^2 is provided at the domain bottom and a constant temperature of 27ºC at the top surface. The formation temperature is initialized at 27°C (80°F) at the surface with a temperature gradient of 0.0289ºC/m and extends to a depth of 6100. m with a temperature of 203°C. The vertical spacing between the injection perforation interval and extraction perforation interval is 60. m with circulation fluid injection taking place at 4237. m depth and extraction taking place at 4297. m depth. The working fluid circulation rate was 6.31 kg/s and the injection fluid temperature into the formation was 27ºC (80ºF). Slug tracer, having similar properties to the working fluid water, was injected for 1.0 day after which working fluid circulation was carried out. From the moment analysis of tracer return data, the mean residence time of the working fluid and the volumetric swept volume were determined (Shook, 1998). The results of the base case are discussed in the following section.

In Figure 2, the effluent fluid temperature from the dual perforation interval case is plotted and in Figure 3 the ideal work extraction rate history is plotted. At the end of 5 years, the effluent fluid temperature is 78.6ºC and the ideal work

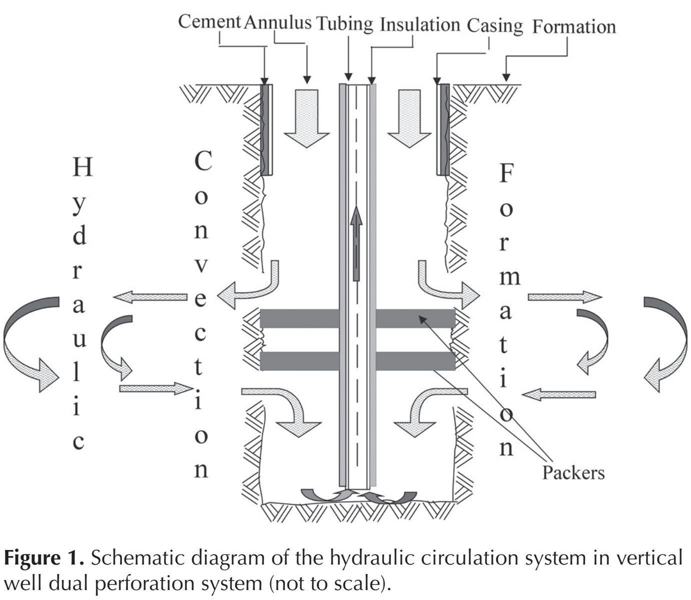

Figure 1. Schematic diagram of the hydraulic circulation system in vertical well dual perforation system (not to scale).

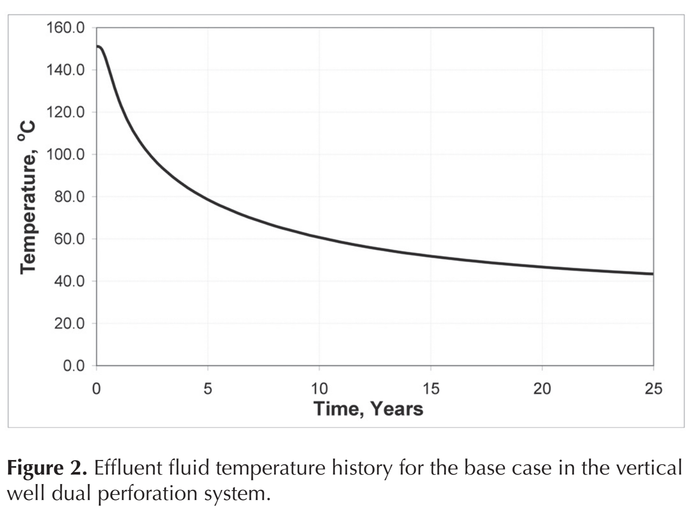

Figure 2. Effluent fluid temperature history for the base case in the vertical well dual perforation system.

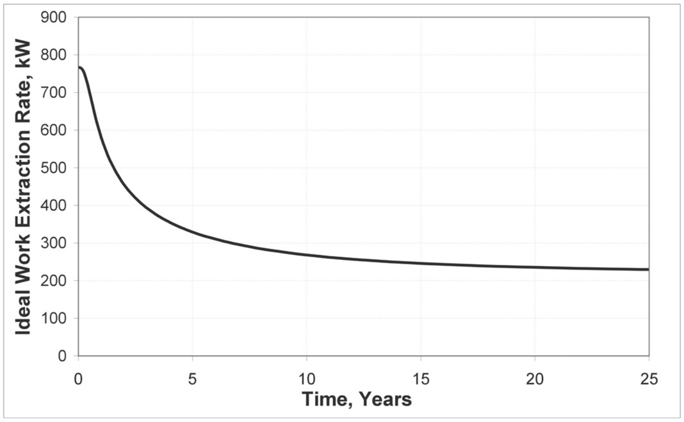

Figure 3. Ideal work extraction rate for the base case in vertical well dual perforation system.

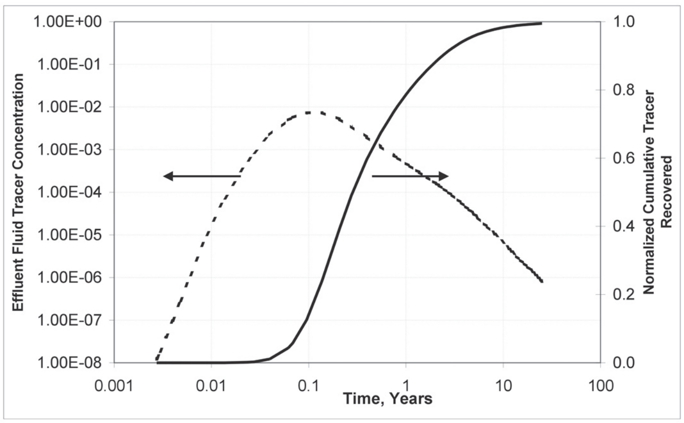

Figure 4. Effluent tracer concentration and normalized cumulative tracer recovered histories for the base case in vertical well dual perforation system.

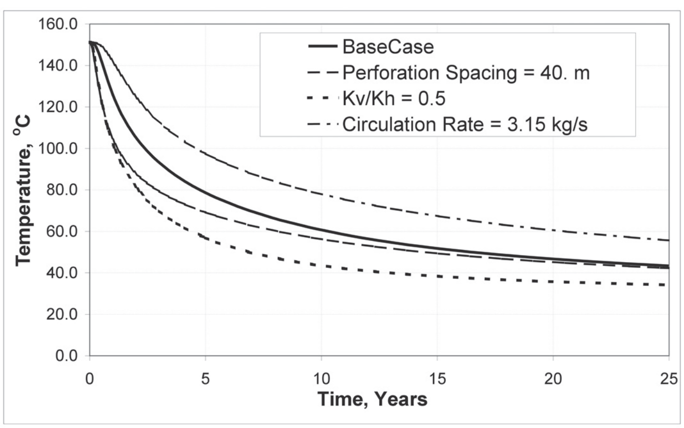

Figure 5. Effects of parameter variation on effluent fluid temperature in vertical well dual perforation system.

rate is 329 kW. In Figure 4, the normalized cumulative tracer recovered and the instantaneous tracer concentration in the effluent fluid is plotted. The tracer is used to trace the injectate and from the first moment analysis of extended tracer return data (extrapolation beyond 25.0 years), the mean residence time was determined to be 1.14 year and the formation swept volume was 2.27e5 m^3. The study conducted by Herling et al.

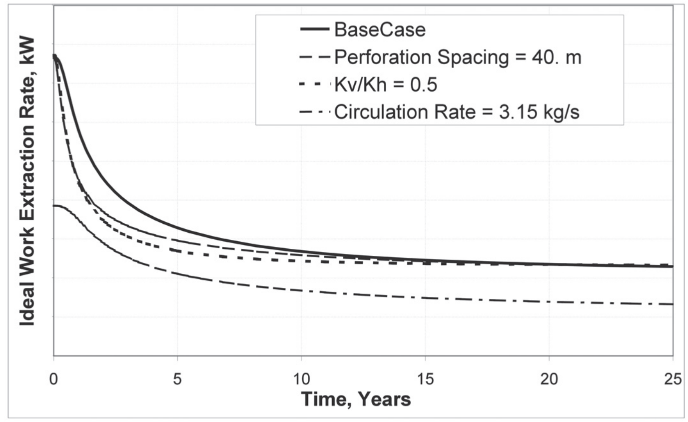

Figure 6. Effects of parameter variation on ideal work extraction rates in vertical well dual perforation system.

(2000) identified the circulation rate, vertical to horizontal permeability and the injection/extraction screen spacing to be important in their forced hydraulic circulation system for remediation applications. Hence, in order to determine if these parameters had a significant effect on the effluent fluid temperature and ideal work rate, a sensitivity study was conducted. Figure 5 and Figure 6 show the comparison of effluent fluid temperature and ideal work rate history plots for base case and cases with halved circulation rates, five times higher vertical to horizontal permeability and two-third times lower injection/extraction perforation spacing. Comparison of effluent fluid thermal energy variables will be done at 5 years. In Table 1, a summary of the parametric variation study results is presented. With increased vertical to horizontal permeability, the effluent fluid temperature fell to 56.9°C and the ideal work was 269.8 kW. The increased vertical permeability led to an increased cross flow and early breakthrough of injection fluid and hence resulted in low effluent fluid temperature and ideal work rates. With reduced circulation rate, the temperature increased to 97.4°C from 78.6°C but the ideal work rate reduced to 211.0 kW from 329.0 kW in the base case. The lower mass rate increased the temperature but reduced the ideal work rate. When the perforation interval vertical spacing was reduced from 60. m to 40. m, the effluent fluid temperature had dropped to 69.2°C and the ideal work rate had dropped to 296.2 kW. The closer the injection and extraction perforations and the greater the vertical to horizontal permeability ratio, the worse becomes the breakthrough and short-circuiting of injectate. The vertical spacing is constrained because saturated sedimentary beds

Table 1. Summary of the parametric variation study in vertical well dual perforation system.

Case Identifier	Vertical Spacing between the perforation intervals, m	Permeability ratio, Kv/Kh	Circulation Rate, kg/s	Tracer Residence Time, Yrs	Volumetric swept Pore Volume, m^3	Effluent Fluid Temperature, °C	Ideal Work Rate, kW
Basecase	60	0.1	6.31	1.14	2.27E+05	78.6	329.0
Kv/Kh ratio	60	0.5	6.31	0.57	1.14E+05	56.9	269.8
Circulation rate	60	0.1	3.15	2.50	2.50E+05	97.4	211.0
Perforation Spacing	40	0.1	6.31	0.95	1.89E+05	69.2	296.2

such as aquifers are generally limited in their vertical thickness to 30-100 m. Out of all the cases, the base case appears to be the optimal case with an effluent temperature of 78.6°C and an ideal work rate of 329.0 kW.

Vertical Well Multilateral Doublet

An alternative approach of having a vertical well with multilaterals was also taken up for the study. The reservoir model used for the multilateral doublet is identical to the description given in the vertical well dual perforation system. In a conservative approach, the effluent fluid temperature and ideal work extraction rate is determined at the lateral well perforation production conditions assuming that the heat losses from the bottom hole to the surface is negligible with reasonably good insulation and negligible friction pressure losses. The main well is located at the center of the domain with the laterals extending symmetrically about the main well. The injection lateral is located above the producer lateral well. A schematic diagram of the vertical well multilateral doublet is given in Figure 7. A parametric sensitivity study was done to determine the effect of the various parameters on the effluent fluid temperature history and ideal work rates. The results of the multilateral well numerical study are discussed in the following section.

Case A is constructed with the following specifications. The injector lateral well extends horizontally to 22.5 m in either

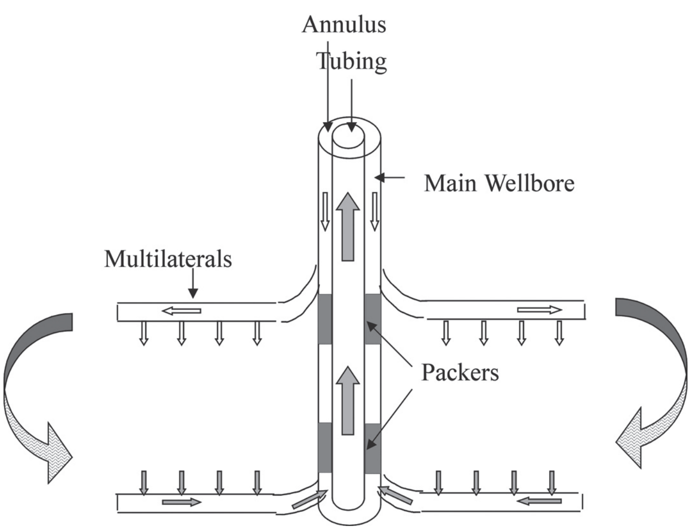

Figure 7. Schematic diagram of the vertical well multilateral doublet system. (not to scale)

Table 2. Summary of the parametric variation study in vertical well multilateral doublet system.

Case Identifier	Lateral Well Length, m	Vertical Spacing of Lateral Doublet, m	Circulation Rate, kg/s	Tracer Residence Time, Yrs	Volumetric swept Pore Volume, m^3	Effluent Fluid Temperature, °C	Ideal Work Rate, kW
A	45	60	6.31	1.100	2.199E+05	78.5	333.4
B	95	60	6.31	1.100	2.199E+05	77.9	333.5
C	145	60	6.31	1.094	2.185E+05	77.3	332.1
D	95	60	12.62	0.584	2.336E+05	60.5	529.3
E	95	60	31.55	0.251	2.505E+05	42.4	920.9
F	145	60	12.62	0.58	2.317E+05	60.4	536.0

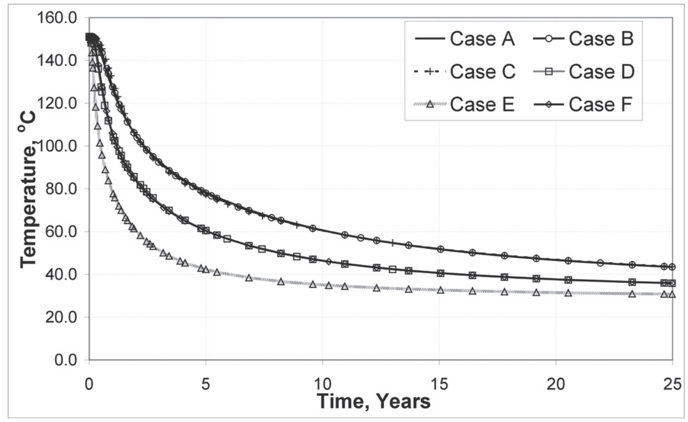

Figure 8. Effects of parameter variation on effluent fluid temperature.

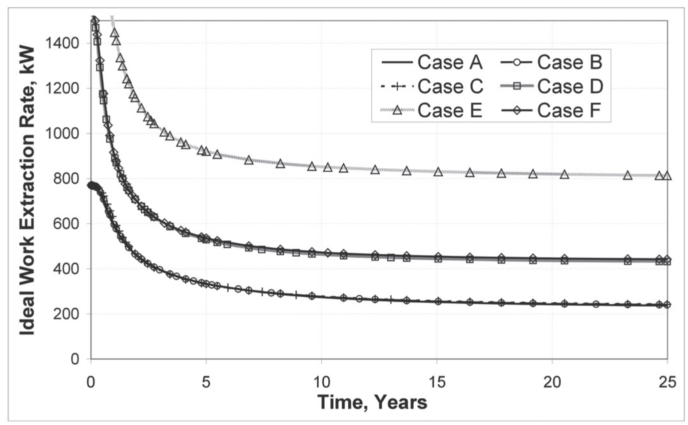

Figure 9. Effects of parameter variation on ideal work rates.

side of the well main and is located at a depth of 4237. m. The producer lateral well extends horizontally to 22.5 m in either side of the main well and is located at a depth of 4297. m. The working fluid circulation rate was 6.31 kg/s and the injection fluid temperature into the formation was 27°C (80°F). The parameters that were varied include the lateral well length and the circulation rate. The vertical spacing between the lateral doublet was constrained to 60. m since this is an application for sedimentary systems, as in aquifers, and represented a realistic maximum possible thickness.

In Table 2, a summary of the parameter data and the results of tracer residence time calculated from the first moment, the injectate swept volume, the effluent fluid temperature and ideal work rate at 5 years are given. The effects of parameter variation on the effluent fluid temperature is given in Figure 8 and the effects of parameter variation on the ideal work extraction rate is given in Figure 9. The results indicate that the multilateral length had an insignificant effect on the effluent fluid temperature and ideal work rates. Comparing the Case A, B and C results with the base case of dual perforation system, it is concluded that with a fixed rate, the lateral well length had an insignificant effect on the effluent fluid temperature and ideal work rate. The reason could be that with increasing lateral well lengths for a fixed circulation rate, the injection pressure would be decreasing since the injection rate per unit length decreases and the effective radius of swept area would be decreasing per injection perforation interval. Hence, as lateral well length increased for a constant circulation rate, the effective swept radius per injection perforation interval on the multilateral well decreased and that resulted in a slight decrease in the temperature from a lateral length of 45 m to 145 m but was not significant. With a constant lateral well length of 95 m, the circulate rate was varied in case D and E. Increasing the circulation rate two times (100%) in case D decreased the fluid temperature from 77.9°C to 60.5°C (22%) and increased the ideal work rate from 333.5 kW to 529.3 kW (58.7%), while in case E an increase of circulation rate by five times (400%) decreased the fluid temperature from 77.9°C to 42.4°C (45.6%) and increased the ideal work rate from 333.5 kW to 920.9 kW (176%). Thus, an optimal balance exists between the circulation rate and the effluent fluid temperature. In case F, the lateral well length is 145 m and the circulation rate is 12.62 kg/s, and comparing cases D and F shows that even at higher circulation rates, the lateral well length did not have a significant effect on the effluent fluid temperature and ideal work rates.

A plot of the effluent fluid temperature and ideal work rate for all cases at the end of 5 years is given in Figure 10 and the region with optimal temperature and ideal work rates, is identified as the optimal region. Cases D and F come under the optimal region. In case E, the temperature is below the optimal temperature zone and even though it has high ideal work rate, the amount of ideal work rate extracted per unit mass of fluid is less. Thus a balance has to be determined between the circulation rate and expected effluent fluid temperatures. The tracer residence times, calculated from the first moment analysis, for the various cases are plotted in Figure 11. The residence time for 6.31 kg/s, 12.62 kg/s and 31.55 kg/s circulation rates are in the range of 1.1, 0.58 and 0.25 years respectively. Taking case F as the best case, the effluent fluid temperature and ideal work rates are 60.4°C and 536 kW at 5 years. The effluent tracer concentration and normalized cumulative tracer recovered histories are given in Figure 12. 99.7% of tracer is recovered at 25 years and the mean residence time is 0.58 years. The fractional flow capacity vs. storage capacity diagrams (Shook, 2003) for the best case multilateral doublet system and the dual perforation interval system are plotted in Figure 13 and are shown to be identical. Approximately 80% of the flow capacity is accounted by 24% of storage capacity. This suggests that only 24% of tracer swept volume is being contacted by 80% of injectate flow. The F-C plot suggests that better ways of having a uniform distribution of the circulation fluid over the swept volume would further enhance the thermal energy extraction process. In Figure 14 and Figure 15 (overleaf), the effluent fluid temperature and ideal work rates are plotted for the best

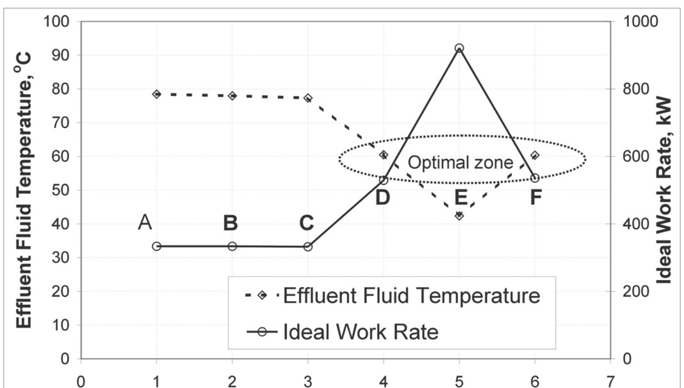

Figure 10. Effluent fluid temperature and ideal work extraction rates at 5 years as a function of parameter variation.

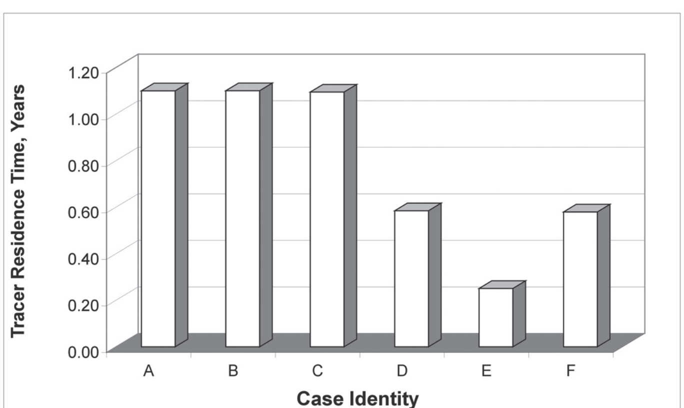

Figure 11. Tracer residence times for the various cases.

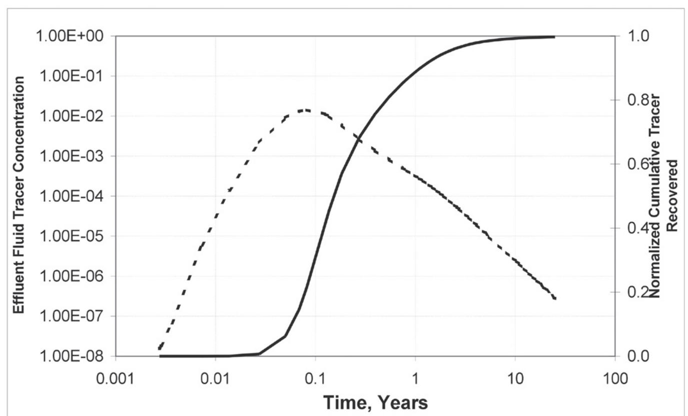

Figure 12. Effluent tracer concentration history for the best case in vertical well multilateral doublet system.

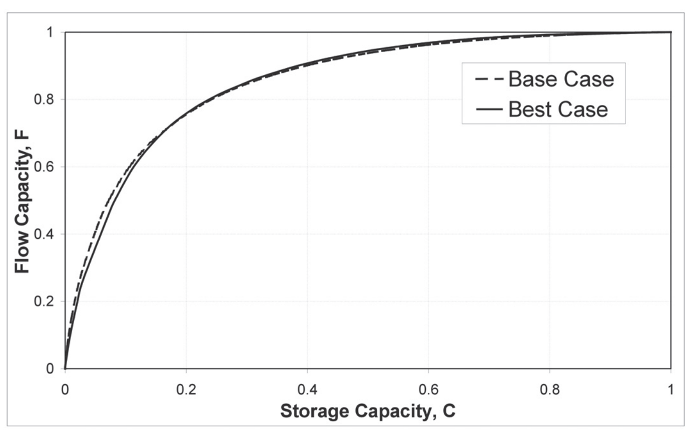

Figure 13. Flow Capacity diagram for the base case dual perforation system and the best case multilateral doublet system.

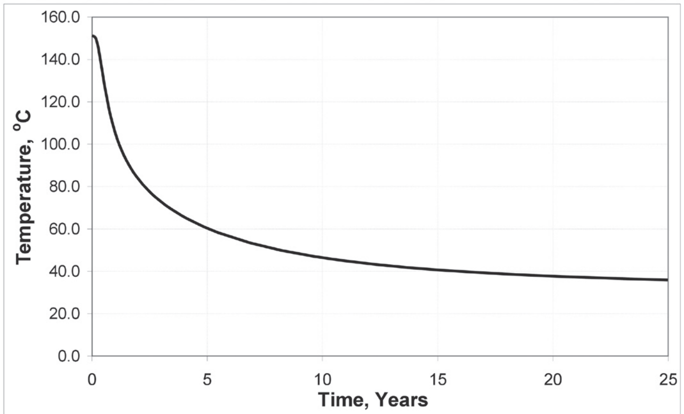

Figure 14. Effluent fluid temperature history for the best case in vertical well multilateral doublet system.

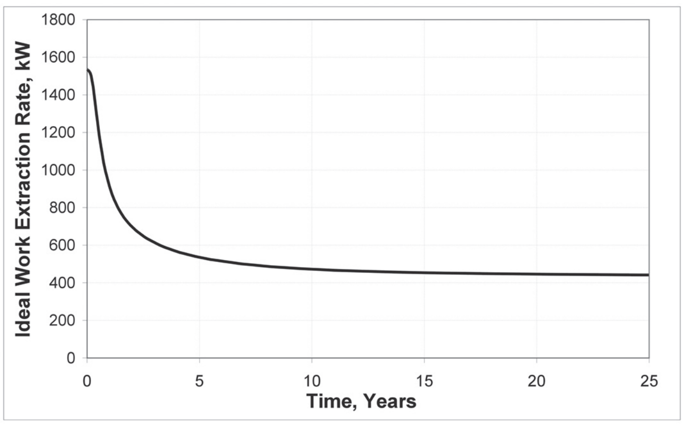

Figure 15. Effluent fluid ideal work extraction rate history for the best case in vertical well multilateral doublet system.

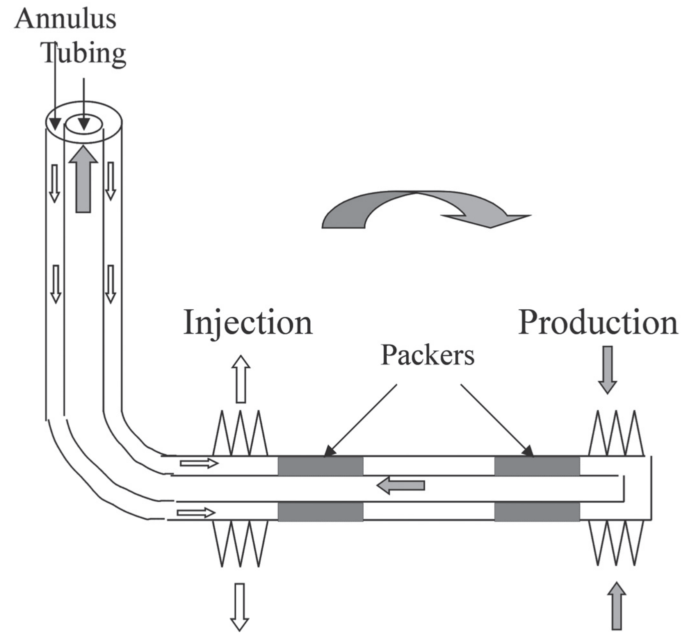

Figure 16. Schematic diagram of the horizontal well dual perforation system.

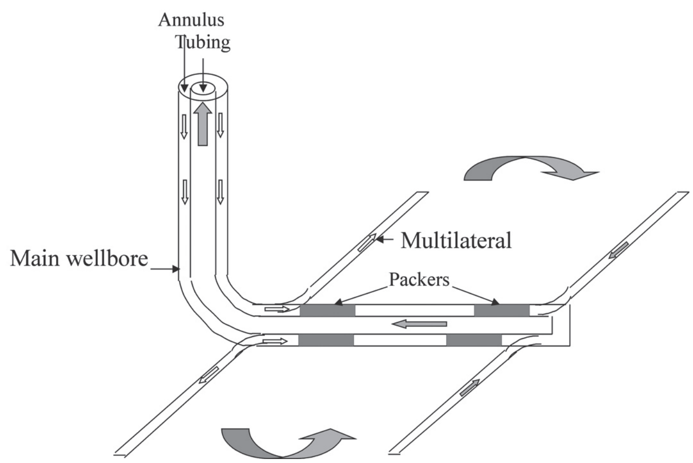

Figure 17. Schematic diagram of horizontal well multilateral doublet system.

case. The best case effluent fluid temperature of 60.4°C at 5.0 years is not in the range required for power generation but considering that the bottom hole injection temperature (27°C) did not consider the heat gain due to thermal conduction while flowing downward, and an increase of 33.4°C in fluid temperature was obtained from a 60. m lateral well spacing in sedimentary bed, it would be suggested that the vertical well multilateral doublet appears to be a promising technique for enhanced geothermal system.

Future Study

Horizontal Well Dual Perforation and Multilateral Doublet Systems

The study of the vertical well dual perforation system and multilaterals were constrained in the injection/production doublet separation distance because of the sedimentary bed thickness. Therefore, an alternative approach of having a horizontal well with dual perforation intervals will be considered for future study. A schematic diagram of the horizontal well dual perforation system is given in Figure 16. The horizontal well dual perforation system consists of an injector perforation and a producer perforation in a horizontal well. One of the failings of the vertical well dual perforation system was the relatively close spacing of the perforation intervals, which was constrained because of the saturated sedimentary bed thickness. In a horizontal well, the perforation intervals could be placed at much longer distances and that might enable creating higher temperature fluids with higher ideal work rates.

Another case that will be further studied would be the Horizontal well multilateral doublet approach shown schematically in Figure 17. The vertical spacing between the laterals was constrained in the vertical well, while in the horizontal well it could be extended further. Similar to the vertical well multilateral doublet approach, laterals extend from the horizontal well, while one serves as an injector the other serves as a producer. Intuitively, it appears that the horizontal well multilateral doublet system would give the best effluent fluid temperature and ideal work rates.

Summary & Conclusions

Engineering Geothermal Systems is one of the important priorities in the industry for sustained geothermal energy production. This work was done to investigate the alternatives of using advanced single well technologies for creating cost effective ways of extracting thermal energy and studying the viability for power generation.

The base case vertical well dual perforation system had an effluent fluid temperature of 78.6°C and ideal work rate of 329 kW at 5 years evaluated at bottomhole production conditions. The perforation intervals were constrained to 60 m. A parametric sensitivity study conducted suggested that the major issue of concern here would be the short spacing of the perforation intervals with high vertical to horizontal permeability, resulting in little resistance to breakthrough and short circuiting of injectate near the wellbore surface.

The analysis of the vertical well multilateral doublet approach suggested it to be promising for enhanced geothermal systems. The vertical spacing of the lateral wells was constrained to 60 m. The lengths of the laterals, in the range of this study 45~145 m, had an insignificant effect on the effluent fluid temperature and ideal work while the circulation rate, in the range of 6.31~31.55 kg/s, had a significant effect on the effluent fluid temperature and ideal work rate. For a fixed circulation rate, as the lateral length increased the injection pressure would be decreasing since the injection rate per unit perforated length decreases. As the circulation rate increased, the effluent fluid temperature decreased and the ideal work rate increased. The higher temperatures are favorable for power generation and hence a balance has to be established between the circulation rates and the ideal work extraction rates. An effluent fluid temperature of 60.4°C (increase of 33.4°C) in working fluid temperature and an ideal work extraction rate of 536 kW at 5 years was obtained from a 60. m lateral well spacing in sedimentary bed using the best case multilateral well system. Based on these results, it would be suggested that the vertical well multilateral doublet appears to be a promising technique for enhanced geothermal system and further study is recommended to do a comprehensive analysis of vertical well multilaterals.

The thickness of the saturated sedimentary beds places a constraint on the vertical spacing between the injection and extraction intervals. Therefore, the dual perforation system and multilateral doublet in a horizontal well intuitively appears to be more promising for power generation than vertical well and wellbore heat exchanger since the significant parameter, the distance between the injection/extraction intervals, would become unconstrained and a larger in situ rock-working fluid contact volume would become possible.

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