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PARAMETRIC SENSITIVITY STUDY OF OPERATING AND DESIGN VARIABLES IN WELLBORE HEAT EXCHANGERS

Gopi Nalla, G. Michael Shook, Gregory L. Mines, K. Kit Bloomfield

Idaho National Engineering and Environmental Laboratory
Idaho Falls, ID 83415-2107
nallg@inel.gov

ABSTRACT

A numerical study was conducted to evaluate the potential for using a Wellbore Heat Exchanger model for power generation. Variables studied included operational parameters such as circulation rates, wellbore geometries and working fluid properties, and regional properties including basal heat flux and formation rock type. Energy extraction is strongly affected by fluid residence time and heat transfer contact area, and by formation thermal properties. Water appears to be the most appropriate working fluid. Aside from minimal tubing insulation, tubing properties are second order effects.

On the basis of the sensitivity study, a Best Case model was simulated, and results compared against existing, low-temperature power generation plants. Even assuming ideal work conversion to electric power, a wellbore heat exchange model cannot generate 200 kW at the onset of pseudo-steady state. Using realistic conversion efficiency, the method is unlikely able to generate 50 kW.

INTRODUCTION

Although Engineered Geothermal Systems (EGS) are typically thought of as being either permeability-limited or fluid-limited, an extreme EGS condition is one in which there is neither sufficient permeability to induce flow nor working fluid to circulate through the rock formation. Under these conditions, heat extraction via circulation in a wellbore has been proposed as a means of geothermal power generation and/or for direct use applications (Kohl et al., 2002; Lund, 2003).

The wellbore heat extraction (WBHX) concept can be described as follows. Cold fluid is injected into and circulates down the annulus, up the tubing, and is produced at the surface. There exists no contact between the working fluid in the well and the reservoir, other than heat conduction across the well perimeter itself. Figure 1 shows a schematic diagram of the wellbore heat exchanger model. The wellbore consists of the tubing, insulation, casing, and cement. The well is cased and cemented to a certain depth, and the remaining portion of the well is retained as an open hole. The tubing is insulated and extends to the wellbore bottom. The fluid is injected in the annulus, and as it descends it gains heat from the formation, and the hot fluid then rises up through the tubing and is produced. Power generation can take place either at the surface or downhole; as is shown in a later section, the temperature differences are small because fluid residence time in the tubing is small.

We have undertaken an extensive sensitivity study to evaluate the potential for power generation using the wellbore heat extraction concept. In addition to operational parameters (e.g., circulation rates, well geometry and depth, working fluids), we also examined regional variables such as heat flux and formation thermal properties. This work is an extension of preliminary studies conducted at Sandia National Laboratory (J. Finger, personal communication, 2003), and comprises a comprehensive numerical evaluation of the proposed method for geothermal power production.

NUMERICAL MODEL

A preliminary study was conducted at Sandia National Laboratory, using their wellbore simulator, GEOTEMP (Mondy and Duda, 1984). Due to certain restrictions inherent in GEOTEMP, we elected to extend that study using TETRAD (Vinsome and Shook, 1993). We first ran a set of validation cases, in which TETRAD and GEOTEMP results were compared. After adequate validation cases were run, we then conducted the sensitivity study using TETRAD. Details of the validation exercise can be found in Nalla et al. (2004).

Base Case Description

A realistic wellbore heat exchanger model was constructed as a base case for the sensitivity study. It consists of a 311 mm (12 ¼ in.), vertical well drilled to 5593 m (18,350 ft). The top 762 m (2500 ft.) of the well is cased and cemented; the balance of the well is open hole. Tubing extends to the bottom of the wellbore. The tubing is 6.35 mm (0.25 in.) thick with internal diameter of 76 mm (3 in.), and is covered by 6.35 mm (0.25 in.) insulation. The tubing and casing are made of steel, the insulation is made of magnesia, the formation has properties typical of sandstone, and water is the working fluid. Well depth was calculated assuming a surface temperature of 27ºC, a bottomhole temperature of 350ºC, a basal heat flux of 0.1 W/m^2, and a uniform formation thermal conductivity of 1.73 W/m°C. The properties selected for the base case are considered representative of geothermal drilling and completion operations, but are varied in subsequent sensitivity studies. Base case properties are summarized in Table 1.

Table 1: Base case Description

Well Geometry	
Tubing inner diameter, in.	3.
Tubing outer diameter, in.	3.5
Insulation outer diameter, in.	4
Casing inner diameter, in.	9.
Casing outer diameter, in.	9.625
Wellbore diameter, in.	12.25
Well Depth, m	5593
Parameters	
Basal Heat Flux, W/m^2	0.1
Formation Thermal conductivity, W/m°C	1.73
Formation volumetric heat capacity, kJ/m^3°C	1810.7
Working fluid volumetric heat capacity, kJ/m^3°C	4186.8
Insulation Thermal Conductivity, W/m°C	0.07
Circulation Rate, gpm	100
Surface Temperature, ^{o}C	26.7
Bottom Hole Temperature, ^{o}C	350

The wellbore is originally filled with water that is in thermal equilibrium with the formation. At t = 0 a constant volumetric rate of 6.31 kg/s (100 gpm) is injected in the annulus and fluids are produced from the tubing. The simulation time period was selected as 5 yrs (1826 days).

The results discussed here are the produced fluid temperature and ideal work histories. Ideal work was calculated from the fluid enthalpy and entropy at wellhead pressure and temperature, with rejection to ambient conditions. An ideal heat engine would be able to convert all of the ideal work 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. We discuss realistic conversion efficiency using the optimum parameters in the final section.

The produced fluid temperature history for the base case is given in Figure 2. A maximum produced temperature of 253ºC is observed at approximately 0.1 days, resulting from production of fluid originally at the well bottom. The temperature falls quickly, and enters pseudo-steady state (pss) behavior at about 500 days. We define pseudo-steady state as the period wherein the temperature decline is linear and small. At the onset of pss, effluent temperature (T_{pss}) is approximately 84ºC, and declining at 0.006ºC/day. In Figure 3 the ideal work extraction rate history plot is shown. At pseudo-steady state, ideal work is 129 kW, and is declining by approximately 22 W/day.

SENSITIVITY STUDIES

From the base case model described above, we performed a comprehensive sensitivity study of formation properties and operational variables, and how they affect effluent temperature and ideal work histories. This study included an analysis of the wellbore geometry, working fluid

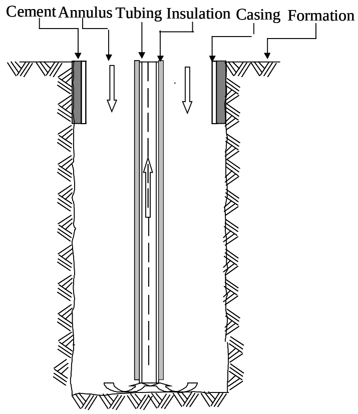

Figure 1: Schematic diagram of Wellbore Heat Exchanger (WBHX)

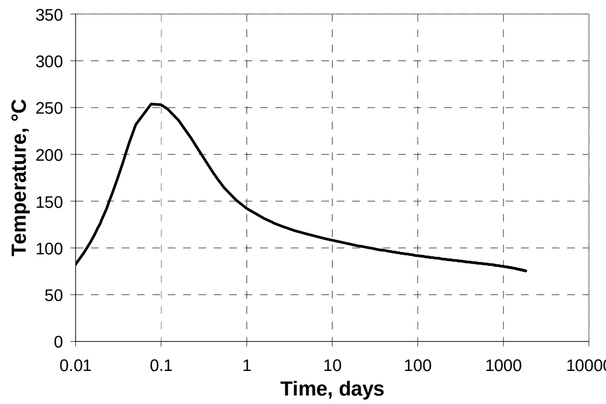

Figure 2: Produced fluid temperature history for the base case

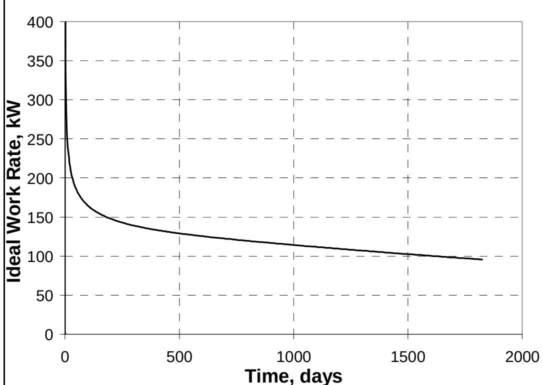

Figure 3: Ideal work extraction rate history plot for the base case

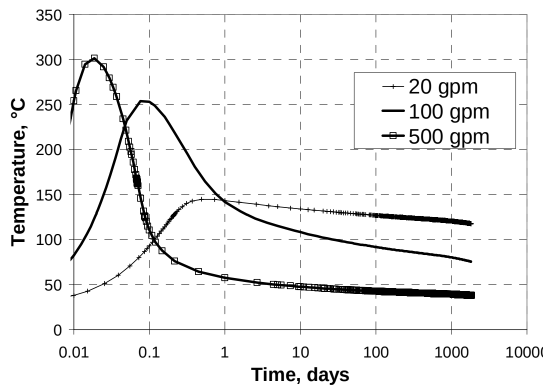

Figure 4: Fluid return temperature histories for the three circulation rates

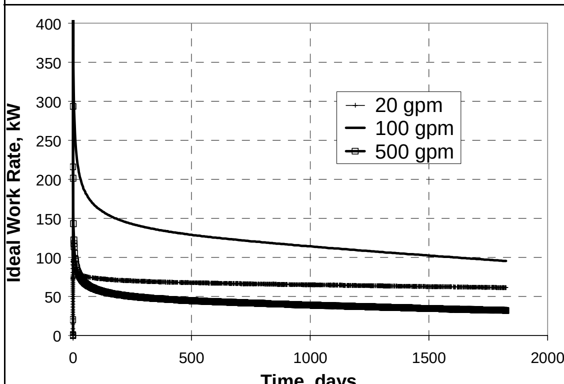

Figure 5: Ideal work extraction rate history for the three circulation rates

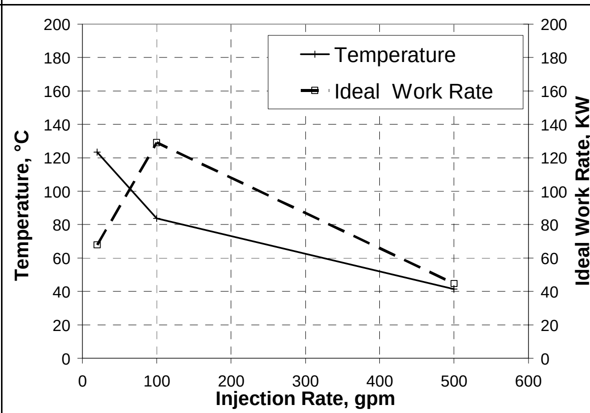

Figure 6: Produced fluid temperatures and ideal work as a function of circulation rates at the onset of pseudo steady state.

properties and circulation rate, and "regional" properties of heat flux and formation rock type. The range over which variables were perturbed are summarized in Table 2.

Circulation Rates

Three circulation rates were used: 1.26 kg/s (20 gpm), 6.31 kg/s (100 gpm), and 31.5 kg/s (500 gpm). Fluid return temperature histories for the three circulation rates are shown in Figure 4. Reductions in maximum temperature observed are due to increased mixing at lower injection rates. Pseudo-steady state temperatures range from 42-125ºC. Variations in effluent temperature are due to the fluid residence time: the larger the residence time, the higher the produced temperature. This can be misleading, however. Figure 5 shows the ideal work extraction rate history for the three circulation rates. Ideal work is a function of both effluent temperature and circulation rate. These work to offset one another, so there is an optimum circulation rate that balances the adverse effects of low circulation with low effluent temperatures at high rates. Figure 6 is a plot of the produced fluid temperatures and ideal work as a function of circulation rates at pss. This plot shows that the optimal circulation rate among the three cases studied was 6.309 kg/s (100 gpm) since the ideal work extraction rate is a maximum.

Table 2: Sensitivity study parameters and ranges of the analysis.

Parameter	Range
Circulation Rate, gpm	20, 100 & 500
Wellbore diameter, in.	12.25 & 26.0
Tubing insulation thermal conductivity, W/m°C	0.07, 0.007 & 0.0
Tubing outer diameter, in.	3.5 & 5.0
Working fluid vol. heat capacity, kJ/ m^3°C	2093., 4186., 8374. & 41868.
Heat flux (W/m^2)	0.1, 0.2 & 0.5
Formation Types (or, more appropriately, ranges of thermal conductivity and diffusivity representative of most rock types)	Berea Sandstone Limestone Boise Sandstone Bandera SS Shale Rocksalt Tuffaceous SS

Wellbore Diameter

Recognizing that residence time strongly affects ideal work rate, a logical modification to the wellbore is to increase its diameter. For a fixed circulation rate, this results in increased residence time, more time for heat transfer, and therefore increased effluent temperature. We varied the wellbore diameter from the base case value of 311 mm (12 ¼ in.) to 660.4 mm (26 in.). Temperature histories for these runs are given in Figure 7. Despite increasing residence time by a factor of 4.5, T_{pss} differs by only 11ºC, a 13% increase. Ideal work at pss (not shown) increases by a factor of 1.39 with the larger wellbore. Thus, while increasing wellbore diameter enhances energy extraction, the improvements are likely offset by increased cost of drilling and casing the larger well.

Tubing Properties

Tubing properties were varied to see what effect they had on produced temperature. The tubing insulation was changed to a perfect insulator in one study, and tubing size was increased in another. Temperature histories summarizing these studies are given in Figure 8. In short, tubing properties proved to be of secondary importance to energy extraction efficiency.

Working Fluid

Volumetric heat capacity of the working fluid has also been analyzed. Water was our original working fluid, with a volumetric heat capacity (ρCp) of approximately 4168 kJ/m^3ºC at standard conditions. We analyzed the effect of different working fluids by independently varying fluid density and specific heat. Transport properties of the fluid (e.g., viscosity) were neglected in this study since friction drop, flow regime, etc. were also ignored and heat conduction in the advecting fluid is negligible. Values for working fluid density and specific heat are given in Table 3.

Table 3: Thermal properties used for the working fluid sensitivity study

Case No.	Fluid Density, kg/m^3	Specific Heat kJ/kg.°K	Vol. Heat Capacity, kJ/m^3°K
A	1000	4.1868	4186.8
B	1000	41.868	41868
C	2000	4.1868	8373.6
D	2000	20.934	41868
E	500	4.1868	2093.4

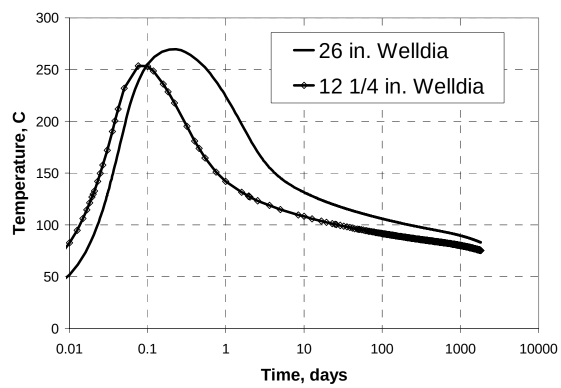

Figure 7: Temperature histories for varying wellbore diameters

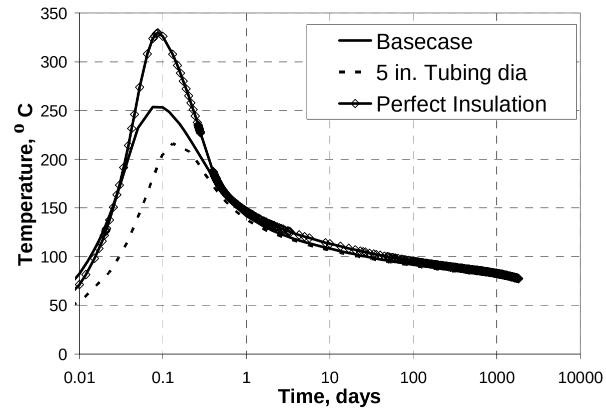

Figure 8: Temperature histories for different tubing properties (diameter & insulation K)

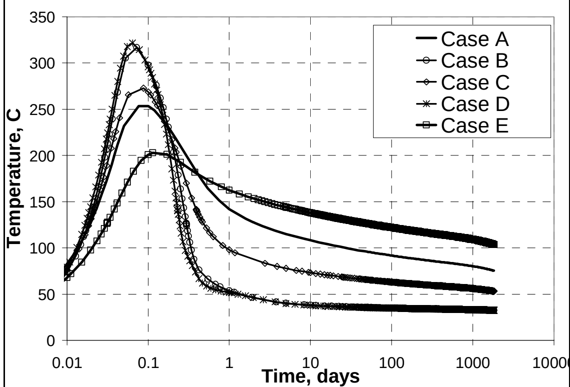

Figure 9: Temperature histories for different working fluid cases

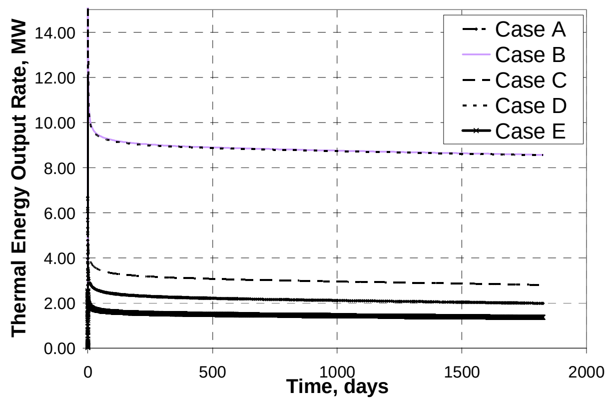

Figure 10: Thermal energy production rate histories for different working fluid cases

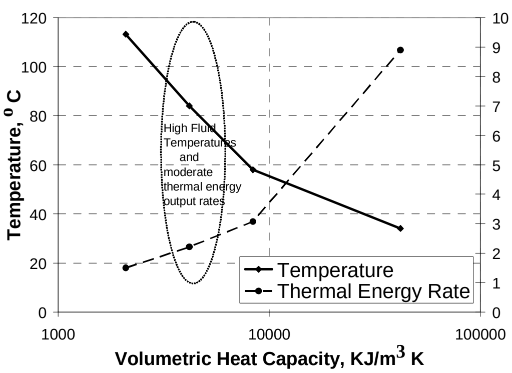

Figure 11: Temperature and thermal energy extraction rates vs. volumetric heat capacity at onset of pseudo steady state

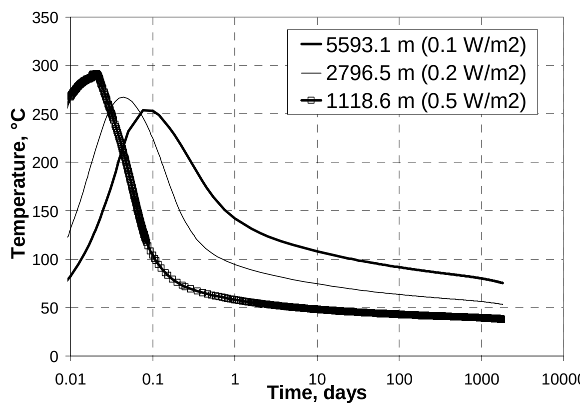

Figure 12: Temperature histories for the three cases of heat flux

Results from this sensitivity study are summarized in Figures 9-11. Temperatures at pss range from 113.2ºC in the case of low volumetric heat capacity (ρCp halved) to 34ºC for Cases B and D (ρCp increased tenfold). The similarity in temperature histories for cases B and D demonstrates that volumetric heat capacity, ρCp, not ρ or Cp independently governs energy extraction.

Since working fluid properties affect ideal work (which is based on enthalpy and entropy specific to the working fluid), it was not calculated; instead, thermal energy production rate is plotted in Figure 10. Figures 9 and 10 show an interesting paradox: fluids with larger volumetric heat capacity have lower temperatures but larger thermal energy density. This is summarized in Figure 11, which illustrates a fundamental problem in identifying the optimum working fluid. Work extraction potential is measured against a rejection temperature; there is a minimum fluid temperature for which energy can be extracted. Given the pss temperature results in this study, it appears that water is nearly the ideal working fluid.

Basal Heat Flux

Recognizing the WBHX concept is not tied to any particular geologic region, two sensitivity studies on "regional" parameters were also conducted. In the first study, sensitivity to basal heat flux was studied. Basal heat flux was varied between 0.1 W/m^2 to 0.5 W/m^2. In all cases, bottomhole temperature was maintained at 350ºC, so varying the heat flux is equivalent to expanding or contracting the well depth. Well depths vary from 5593 m for a heat flux of 0.1 W/m^2, 2796.5 m for 0.2 W/m^2, and 1119 m for 0.5 W/m^2. Since the surface and bottomhole temperatures are fixed, initial temperature gradients in the formation vary accordingly.

Temperature histories for the three cases of heat flux are given in Figure 12. At pss, the produced fluid temperatures were 83.7°C for a heat flux of 0.1 W/m^2, 58.5°C for 0.2 W/m^2, and 40.5°C for 0.5 W/m^2. The plot illustrates that, for a fixed maximum downhole temperature, deeper wells yield higher produced fluid temperatures. The fluid residence times and contact surface areas are a function of the wellbore depth. The larger residence time of the circulating fluid and heat transfer area in the deeper well leads to more energy transfer and higher fluid temperature at pss. Power generation follows the same trend: under conditions of fixed bottomhole temperature, lower heat flux, and hence deeper wells is favorable for energy extraction. Of course, economic considerations (neglected in this study) would argue the reverse.

Formation Types

Seven different formation types were selected, and the effects of varying formation thermal properties on the heat extraction process were studied. The thermal properties of the different formations are given in Table 4.

Table 4: Formation Thermal Properties

Formation Type	K W/m°C	ρCp kJ/m³°C	κ, m²/sec	K/√κ, J/m²√s°C
Shale	1.89	1875.7	1.01×10^{-6}	1881
Limestone	1.56	1877.8	8.33×10^{-7}	1709
Berea SS	1.57	1810.7	8.68×10^{-7}	1685
Boise SS	1.41	1576.0	8.92×10^{-7}	1493
Tuffaceous SS	0.69	1469.2	4.69×10^{-7}	1008
Rock Salt	0.60	188.3	3.18×10^{-6}	336
Bandera SS	0.16	181.1	8.6×10^{-7}	173

For convenience, these properties were taken from a compilation of sedimentary and evaporite formation types (Prats, 1982); however, the range of properties is representative of essentially all rock types. Other than formation thermal properties, all other variables are as in the base case. Temperature histories for the various cases are given in Figure 13. As can be seen, the formation with the largest thermal conductivity *and* thermal diffusivity gives the highest fluid temperature. Dependence on both thermal conductivity and diffusivity (which contains conductivity) is because heat transfer from a conductive regime into an advecting regime is proportional to both conductivity and the square root of diffusivity (Carslaw and Jaeger, 1959, p 396). In fact, if the formations are ranked according to decreasing $K/\kappa^{1/2}$ where κ is the thermal diffusivity and K is thermal conductivity, pss temperature histories (and work rates) correlate to that order. This is shown in Figure 14, which shows ideal work extraction rate plotted as a function of $K/\kappa^{1/2}$. This figure

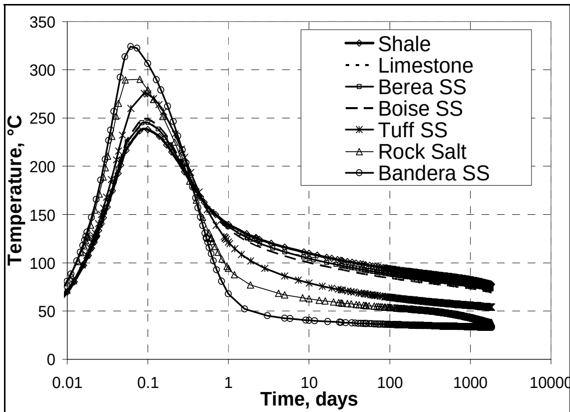

Figure 13: Temperature histories for the various cases

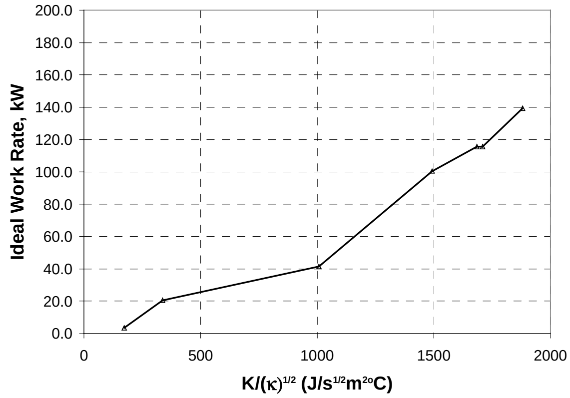

Figure 14: PSS Ideal work extraction rate plotted as a function of $K/\kappa^{1/2}$

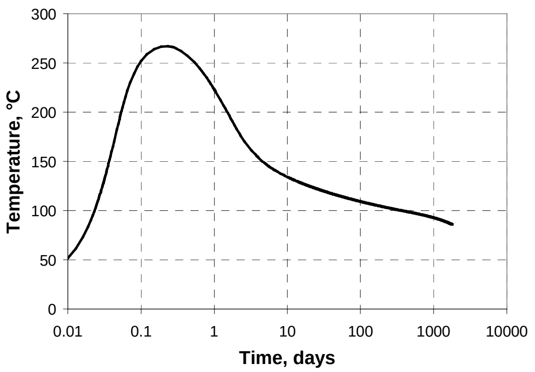

Figure 15: Temperature history for the Best Case

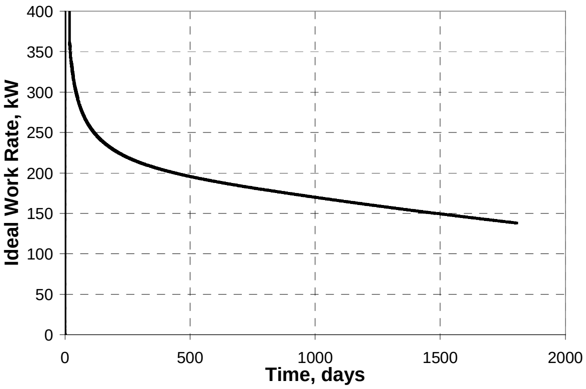

Figure 16: Ideal work extraction rate for the Best Case

demonstrates the formation properties most appropriate for WBHX.

CONSTRUCTION OF A "BEST CASE"

Results of the sensitivity study were used to construct the most optimistic set of parameters for WBHX. That set of parameters is summarized in Table 5. Results of the "Best Case" simulation are given in Figures 15 and 16. At the onset of pseudo-steady state, fluid temperature is approximately 98ºC, and ideal work extraction rate is 198 kW. We believe these results to be optimistic for several reasons, including a 350ºC bottomhole temperature and especially ideal conversion of thermal energy to electric power. It was our intent to identify the most optimistic set of formation and operational properties to estimate the ability to generate power using the WBHX concept.

Table 5: Best Case Description

Well Geometry	
Tubing inner diameter, in.	3.
Tubing outer diameter, in.	3.5
Insulation outer diameter, in.	4.
Casing inner diameter, in.	9.
Casing outer diameter, in.	9.625
Wellbore diameter, in.	26.0
Well Depth, m	5593.
Parameters	
Basal Heat Flux, W/m2	0.1
Formation Thermal conductivity, W/m°C	1.89
Formation volumetric heat capacity, $kJ/m^3.°C$	1875.7
Working fluid volumetric heat capacity, $kJ/m^3.°C$	4186.8
Insulation Thermal Conductivity, W/m°C	0.07
Circulation Rate, gpm	100
Surface Temperature, ^oC	26.7
Bottom Hole Temperature, ^oC	350

What information is available on low-temperature generating facilities is summarized in Table 6 below (taken from http://www.geothermie.de/egec-geothernet/prof/small_geothermal_power.htm). The Conversion Rate, η, in Table 6 is defined as fluid circulation rate, q, required per unit of power, W, or:

$$\eta = \frac{q}{W}$$

Table 6: Commerical low-temperature operating specifications

Plant	Fluid temp. °C	Circulation Rate, gpm	Power generation (kW)	Conversion rate, gpm / kW
Fang, Thai.	115	264	300	0.88
Nagqu, Tibet	110	1,100	1000	1.1
Amedee, Ca.	104	3,200	1500	2.13

Using the operational parameters for Amedee, Ca. (at 104ºC closest to our Best Case in producing temperature), we calculate our maximum expected power generation rate from WBHX as follows.

$$W = \frac{q}{\eta} = \frac{100\text{gpm}}{2.133} < 50\text{kW}$$

That is, for what appears to be the optimum set of operating conditions, the WBHX can generate less that 50 kW at the onset of pseudo-steady state.

SUMMARY AND CONCLUSIONS

A numerical model was developed to investigate the potential for power generation using a wellbore as a heat exchanger. A variety of sensitivity studies were conducted to understand variations in operational and regional properties and how they affect heat transfer. On the basis of this study, the following specific conclusions can be drawn.

- There is a tradeoff between circulation rate and energy extraction rates that implies an intermediate optimum circulation rate that maximizes heat transfer to the circulating fluid.
- For fixed circulation rates, any increases in residence time of the fluid in the wellbore enhances energy extraction. This includes wellbore diameter and/or well depth.
- For fixed bottomhole temperature, lower basal heat flux is better because it leads to deeper wells and, hence, longer residence times.
- Minimum tubing insulation is required, but enhancements to either insulation or changes in diameter affect the process insignificantly.

- Energy extraction is very sensitive to formation thermal properties. Larger thermal conductivities *and* larger thermal diffusivities lead to improved energy extraction.
- Tradeoffs exist between the working fluid's heat capacity and the extraction temperature. Water appears to have optimal or near optimal properties to provide reasonable energy density at acceptable temperatures.
- A Best Case WBHX design uses circulation rates far below any low-temperature power plants, and provides fluid temperature also below plant operations. Even assuming ideal conversion of the thermal energy, a WBHX produces less than 200 kW of power at pseudo-steady state. Using realistic conversion rates, it is likely the WBHX can generate less than 50 kW at pss, and that rate declines with time.

ACKNOWLEDGEMENTS

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