Assessing the Influence of Ground Water Inflow on Thermal Conductive Heating in Fractured Rock

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Abstract

Thermal conductive heating (TCH) is an innovative remediation technology developed for aggressive in-situ non-aqueous phase liquid (NAPL) source zone treatment. Electrical heater wells are used to conductively transfer heat into the subsurface, thereby elevating temperatures and boiling both ground water and NAPLs. The design of a TCH remediation system needs to consider the cooling effect of incoming ground water. Previous studies, which have focused only on porous media, have used numerical modeling to determine the influence of this cooling. Results from these studies show that in some cases, inflowing ground water may delay or prevent the treatment zone from reaching the target temperature. Proposed solutions for mitigating the impact of influent cooling include the installation of impermeable barriers, steam injection wells, or pumping wells at the periphery of the treatment zone.

To date, no study has examined the cooling influence of incoming ground water in fractured rock environments in the context of TCH. In the present study, a new semianalytical solution to the heat equation is derived and utilized to study the influence of fracture properties and ground water flow rates on heat transfer in fractured rock. The semianalytical solution is more computationally efficient than a fully numerical model, permitting a detailed evaluation of parameter sensitivity. In this study, the relative importance of rock type, fracture spacing, fracture aperture, and hydraulic gradient are investigated. Rock properties were concluded to be far less significant than the hydrogeological parameters. In contrast, the subsurface temperature distribution may be entirely governed by the presence of high-aperture fractures, a large hydraulic gradient, or close fracture spacing. In addition to investigating the influence of both rock properties and hydrogeological properties on temperature distribution, two potential methods for mitigating the effect of inflow cooling were investigated. Although the installation of upgradient preheating wells can help to offset the heat loss from the fracture, it appears to be far more effective to simply increase the power of the thermal wells in the treatment area.

Introduction

Of the numerous chemical and physical processes involved in site remediation, many depend strongly on temperature. For various organic contaminants of concern, elevated temperatures bring about decreased non-aqueous phase liquid (NAPL) viscosity, increased contaminant desorption, increased NAPL-air mass transfer (vaporization), and increased water-air mass transfer (volatilization). At very high temperatures (> 100 °C), heat may also stimulate processes such as aqueous oxidation and pyrolysis that destroy contaminants in-situ and reduce the need for above-ground treatment. Although these in-situ destruction mechanisms are typically significant only for non-volatile compounds such as PCBs, they may alone provide 95-99% of the removal in these cases (Baker and Kuhlman, 2002).

In recognition of these benefits, researchers have developed several different approaches to the delivery of heat to the subsurface. Steam-enhanced extraction, originally developed by the petroleum industry, has been applied at both the pilot and full scale in unconsolidated deposits (e.g., Newmark et al., 1998). However, new research on steam injection in fractured rock environments has shown the difficulty of achieving large temperature increases throughout a treatment area (Davis et al., 2005). Another thermal remediation technology, electrical restive heating (ERH), achieves heating by passing an electrical current between large electrodes inserted in-situ. The amount of resistive heat produced is relatively uniform throughout the treatment area, providing heat to low permeability areas that may be missed by steam injection. Because ERH relies on pore water to conduct electrical current, it is applicable only to temperatures below the boiling point of water. ERH has been used to treat some fifty contaminated sites, a selection of which are described by Beyke and Fleming (2005).

Thermal conductive heating (TCH) systems employ arrays of heater wells that provide heat to the subsurface. Inside the heater wells, resistive heating elements radiate heat to the well casing, from where it is transferred away by conduction. Principal advantages of TCH include its relative insensitivity to material permeability, large treatment temperature range, and rapid treatment time. Unlike ERH, TCH does not rely on the ability of the aquifer to conduct electricity. This allows TCH systems to reach temperatures far above the boiling point of water if desired; well temperatures of up to 800 °C may be used to treat especially recalcitrant compounds such as polychlorinated biphenyls (PCBs) at inter-well temperatures of 325 °C (Stegemeier and Vinegar, 2001). The application of TCH has been demonstrated in the field; since the technology's commercialization in the mid 1990s, approximately 20 sites have been treated with TCH, including sites contaminated by chlorinated solvents (e.g., Lachance et al., 2006), coal tar (e.g., Baker et al., 2006), and PCBs (e.g., NFESC 1998). In addition, laboratory studies have shown the ability of TCH to remove elemental mercury from soils (Kunkel et al., 2006).

Several mechanisms may cause a loss of heat from the treatment area during thermal applications. Strong vertical temperature gradients at the ends of each heater element may cause heat to be lost through conduction; wells are typically extended a minimum of two feet beyond the limit of the treatment zone to mitigate this effect (Stegemeier and Vinegar, 2001). In addition, insulating blankets may be placed on the ground surface above the treatment area. The influx of cool ground water may present another source of heat loss. When the temperature of the treatment area is below 100 °C, ground water flow may cause heated water to be carried out of the treatment area, representing a loss of energy. At higher temperatures, cool incoming water must be boiled, causing a delay in the attainment of target temperatures.

Although the cooling effect of incoming ground water may be a governing parameter in the design of TCH systems, few published studies have quantitatively examined its importance in porous media, and none has done so in fractured rock. Elliot et al. (2003) used a commercial reservoir simulator to study the cooling influence of ground water in saturated porous media. They found that the remediation time was largely governed by soil permeability and hydraulic gradient; when these parameters were increased above certain threshold values, treatment temperatures were not reached. In the presence of a large ground water influx, the cooling influence may be mediated by steam injection or the installation of an impermeable barrier at the periphery of the treatment zone (Baker and Heron, 2004). Alternatively, an extra row of heater wells could be used to preheat incoming ground water before it enters the treatment area.

The objective of this study is to present a mathematical screening model that can be used to assess the effect of inflowing ground water on the ability to heat a treatment zone in fractured rock using TCH. Calculations are presented to study the influence of hydraulic gradient, fracture aperture, and fracture spacing on the time to treatment.

Model Development

The fractured rock environment is conceptually modeled using a discrete fracture approach, whereby the location and aperture of fractures are specified directly. Fractures, which have an aperture of e, are assumed to be parallel and evenly spaced by a distance of $2H$. A schematic of the conceptual model is shown in Figure 1.

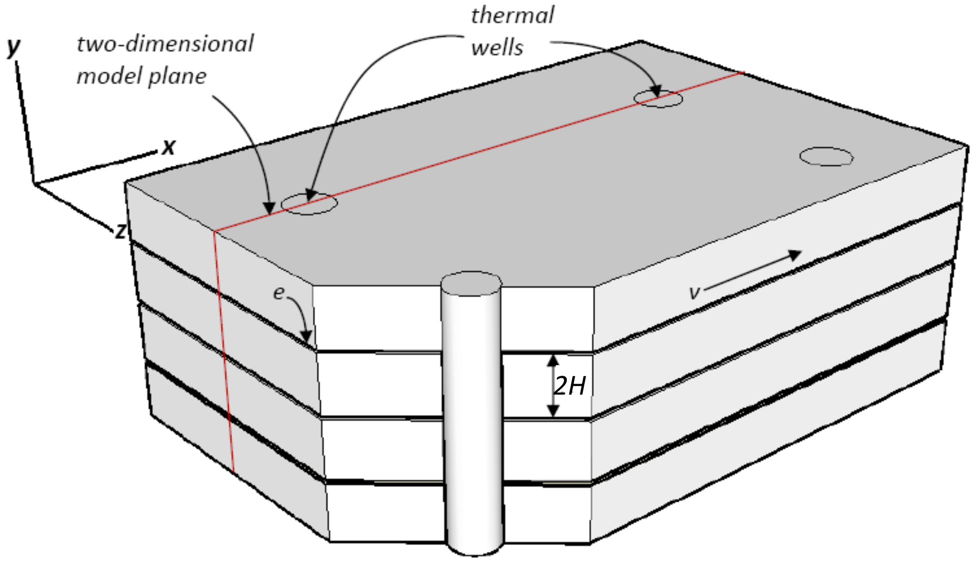

Figure 1: Schematic of conceptual model

In the x-direction, the domain extends to infinity, although the solution technique requires that a finite portion of this domain be discretized, from $x = 0$ to $x = \mathrm{L}$. Heater wells are represented as line sources located at $x = W_i$; any number of heater wells may be modeled. Water flows through the fractures at a uniform velocity v which may be related to a hydraulic gradient by the cubic law (e.g., Witherspoon, 1980). A schematic of the solution domain is shown in Figure 2.

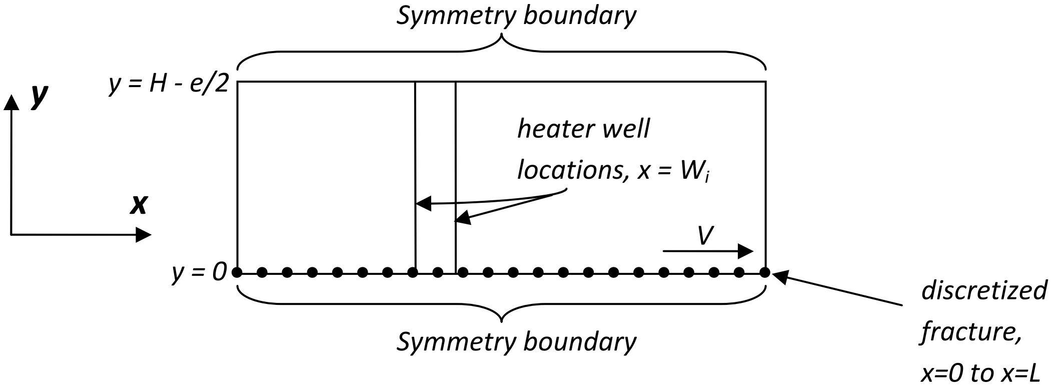

Figure 2: Schematic of solution domain

Using this conceptual model, heat transfer in the rock matrix and in the fracture is governed by separate equations whose solutions are governed by conditions of continuity between the two domains. Heat transfer in the rock matrix is described by (e.g., Özişik, 1980):

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{g(x,y)}{K_r}=\frac{1}{\alpha_r}\frac{\partial T}{\partial t} \tag{1}$$

where K_r is the thermal conductivity of the rock, α_r is the thermal diffusivity of the rock, and g is the strength of energy generation at the point (x,y). The governing equation of the fracture is given by (Cheng et al., 2001):

$$\frac{\partial T}{\partial x}=\frac{2K_r}{\rho_w c_w v e}\left.\frac{\partial T}{\partial y}\right|_{y=0} \tag{2}$$

where ρ_w is the density of water, c_w is the specific heat capacity of water, v is the average velocity of water in the fracture, and e is the fracture aperture.

The system of equations formed by (1) and (2) is difficult to solve analytically. When heat conduction in the rock matrix occurs primarily in the direction normal to the fracture plane, the one-dimensional form of the heat conduction equation may be substituted, and the system is reduced to a more readily solvable system of ordinary differential equations. Using this assumption, Lauwerier (1955) presented a solution applicable to heat transfer between a body of rock and a single fracture. Gringarten et al. (1974) developed a Laplace-space solution for heat transfer between a body of rock and a set of parallel fractures. Lowell (1975) simplified that solution by showing that, for the modelling of hot dry rock geothermal systems, where fracture spacing is typically very large, little error is introduced by considering only a single fracture. Cheng et al. (2001) published a semi-analytical solution that considered two-dimensional conduction explicitly for a single fracture.

When the rock is heated directly, as is the case in TCH, multidimensional heat condition in the rock matrix must be considered. To the authors' knowledge, the semi-analytical solution of Cheng et al. (2001) is the only one to include two-dimensional heat conduction.

Several features distinguish the present solution. First is the explicit modeling of multiple parallel fractures with multidimensional heat conduction in the rock matrix. Although previous solutions have modeled parallel fractures and multidimensional heat conduction, no solution has included both. Second, the present solution allows for inclusion of an unlimited number of heater wells, located at arbitrary coordinates. Third, the solution is given in terms of elementary functions rather than non-elementary functions such as Bessel functions. This reduces computation time and provides increased accuracy when evaluating the temperature at points inside the rock matrix. The solution is not capable of modelling boiling within the fracture, or thermally-induced changes in rock properties.

The solution of (1) is given in a general form by (e.g., Beck et al., 1992):

$$T(x,y,t)=\frac{\alpha_r}{K_r}\int_{\tau=0}^{t}\int_{y'=0}^{H-e/2}\int_{x'=-\infty}^{\infty}G(x-x',y-y',t-\tau)g(x',y',\tau)dx'dy'd\tau \tag{3}$$

where G(x-x',y-y',t-τ) is the Green's function corresponding to a domain bounded by vanishing temperature at x = ± ∞ and second-type boundary conditions at $y = 0$ and $y = H$. Due to its length, an expression for the function is not printed here but may be found from the table of Green's functions published by Beck et al. (1992), who use the notation GX00Y22. The heat source function g(x',y',τ), encompassing the effects of heat exchange with the fracture and heating from the thermal well, is given by:

$$g(x',y',\tau)=g_w\delta(W-x')+\left(K_r\frac{\partial T(x',y',\tau)}{\partial y}\bigg|_{y=0}\right)\delta(y') \tag{4}$$

To solve for the temperature distribution, a Laplace transformation is first applied to equation (3). The transformed equation can then be manipulated to take on the form of a nonhomogeneous Fredholm integral equation of the second kind. In this form, the equation can be solved numerically using straightforward quadrature methods (e.g., Delves and Mohamed, 1985). Finally, a numerical Laplace inversion algorithm (e.g., De Hoog et al., 1982) is used to obtain temperature as a function of time. Details of the solution may be found in Baston (2008).

The special case of zero fracture aperture was verified against an analytical solution by Carslaw and Jaeger (1959, p. 263). Another special case, wherein the rock is not heated by thermal wells but by injection of hot water into the fractures, was qualitatively verified against the solution of Gringarten et al. (1974).

Sensitivity Analysis

A sensitivity analysis was performed to study the relative importance of several hydrogeological parameters (fracture aperture, fracture spacing, hydraulic gradient) and material properties (rock density, thermal conductivity, heat capacity). Rock properties were taken from the compilation of rock thermal data by Čermák and Rybach (1982) and are presented in Table 1. Although the thermal conductivity of sedimentary rocks tends to decrease slightly with temperature (e.g., Clauser and Huenges, 1995), all rock properties were assumed to remain constant with temperature.

Table 1: Material properties for rock types used in simulations. Data from compilation by Čermák and Rybach (1982).

Rock Type	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat Capacity (J/kg·K)
Shale	2.98	2757	1180
Sandstone	3.03	2391	960
Limestone	2.40	2520	890
Dolomite	2.87	2536	920

The "base case" scenario (Table 2) consists of a shale with 500 μm aperture horizontal fractures spaced at 1 m. Ground water flows through the fractures subject to a hydraulic gradient (dh/dx) of -0.005, resulting in an average linear velocity of 67 m/day. Heater wells, located at x = 30 m and x = 33 m, provide a constant heat output of 100 W/m per meter in the *z* direction. This output is equivalent to the spatially averaged flux generated by a row of heater wells, spaced at 3 m, each providing 300 W/m – well within the range attainable by the heater elements in current use (Stegemeier and Vinegar, 2001). Use of an analytical solution (Carslaw and Jaeger 1959, p. 263) shows that, in the absence of cooling from fractures, boiling would occur throughout the interwell zone after 17 weeks of heating.

Table 2: Base case parameters for sensitivity analysis

Rock Type	Shale	**Fracture Aperture**	500 μm
Heater Well Locations	x = 30 m, 33 m	**Fracture Spacing**	1 m
Heater Well Power	g_w = 100 W/m	**Hydraulic Gradient**	-0.005
Initial Temperature	10 °C	**Influent Temperature**	10 °C

Throughout the results that follow, only the temperature at the fracture-matrix interface is presented. Typically, the temperature variation is less than one degree Celsius in the direction normal to the fracture plane, although it can reach four to five degrees for very high ground water inflow rates.

Sensitivity to Hydraulic Gradient

The influence of hydraulic gradient on the temperature profile is very strong, especially after several months of heating. Figure 3 shows the temperature profile in the fracture for eight different values of hydraulic gradient. Several phenomena can be observed in these figures. The first is the strict control that hydraulic gradient exerts over the shape of the steady-state temperature profile. After 6 months of heating, water near the second heater well has begun boiling when the gradient is set to -0.005 but has barely risen ten degrees when the gradient is increased by a factor of five, to -0.0250. The temperature profiles for the different trials can be seen as a “pack” that advances vertically with time. As the pack migrates, the temperature profiles for higher-gradient trials are, one by one, left behind as they reach a steady state. After one month of heating the profiles for dh/dx = 0.04 and dh/dx = 0.025 have already reached steady state, and the profile for dh/dx = 0.015 is close to its final position. After one year has passed, the seven highest-gradient trials have near-steady-state temperature profiles. Figure 4 provides a summary of the minimum and maximum interwell temperatures after one year of heating for all of the gradient trials conducted.

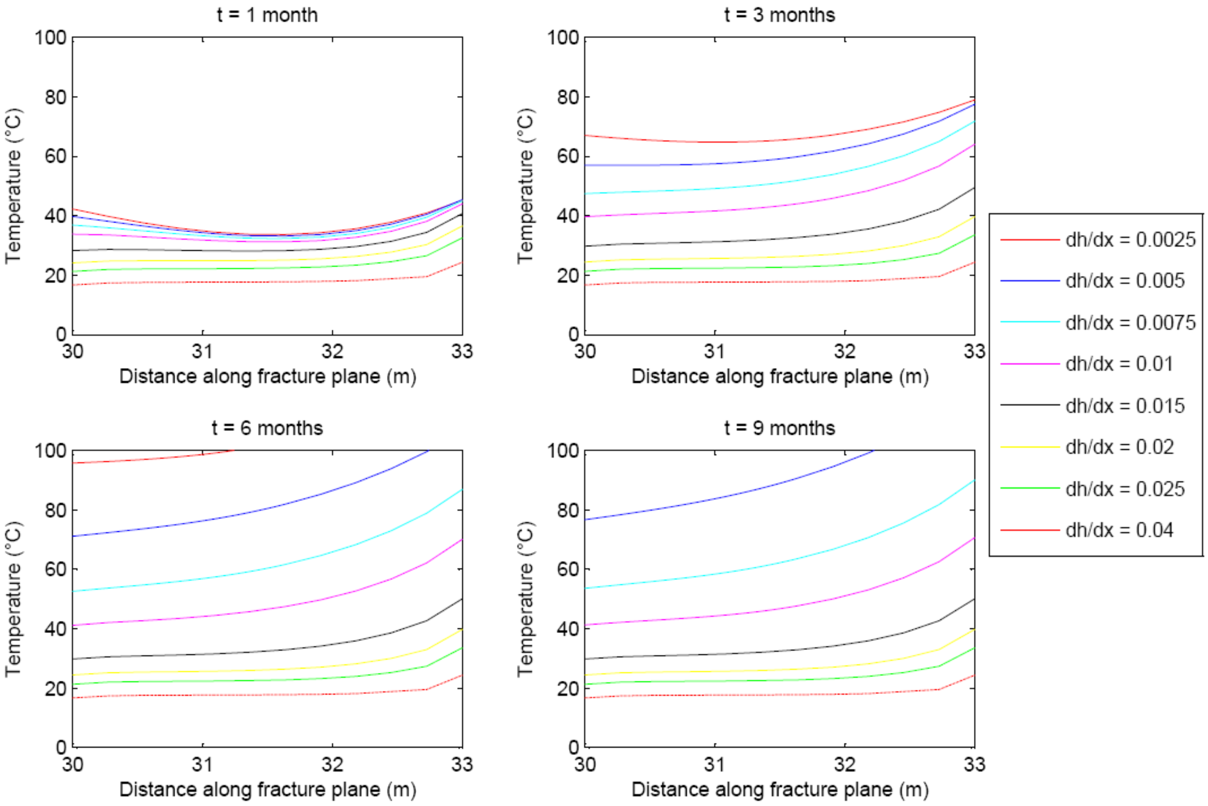

Figure 3: Fracture temperature profiles at four time intervals during heating, showing the influence of hydraulic gradient.

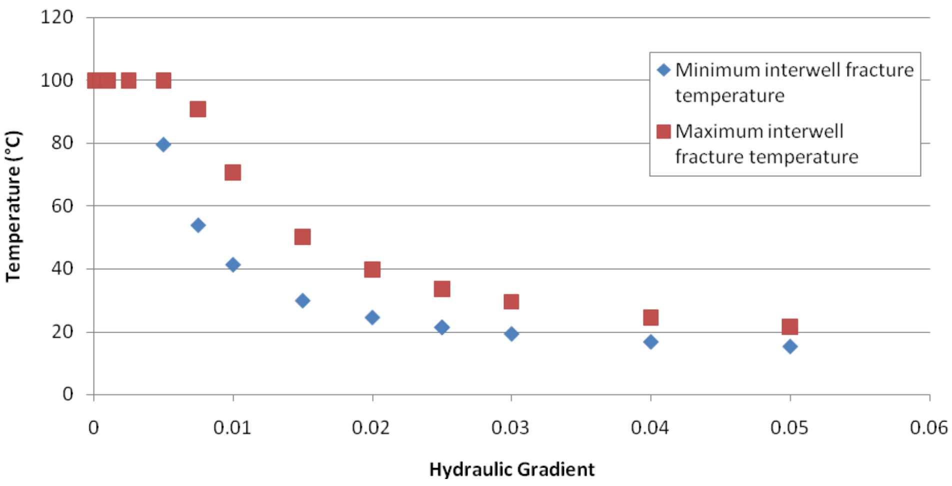

Figure 4: Summary of minimum and maximum interwell temperatures after one year of heating, showing the influence of hydraulic gradient.

Sensitivity to Fracture Spacing

A decrease in fracture spacing causes an effect similar to an increase in hydraulic gradient. When the spacing between significant fracture features is very small, a steady-state temperature profile will be reached after a short period of heating. However, in none of the trials was heating entirely prevented – even with a fracture spacing of 0.25 m, a 10-20 degree temperature rise was observable throughout the fracture. Figure 5 shows the minimum and maximum temperatures in the fracture after one year of heating. For the parameters assigned in this study, all values of fracture spacing in excess of approximately 1.25 m resulted in interwell temperatures of 100 °C.

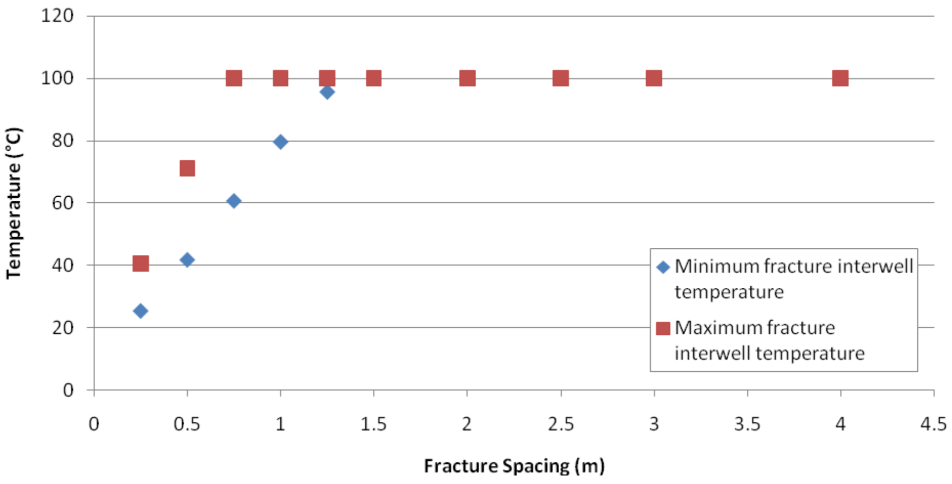

Figure 5: Summary of minimum and maximum interwell temperatures after one year of heating, showing the influence of fracture spacing.

Sensitivity to Fracture Aperture

An increase in the fracture aperture causes the same general effect as an increase in hydraulic gradient or a decrease in fracture spacing. As with the hydraulic gradient, the lowest-aperture fractures show little cooling effect until the aperture is increased above a certain threshold, as determined by the temperature. Figure 6 shows the minimum and maximum temperatures in the fracture after one year of heating. Steady state is reached quickly for the fractures having an aperture greater than 500 µm, and there are few changes in the profiles between one half year and one full year of heating. For the parameters assigned in this analysis, boiling temperatures were reached after one year of heating for all of the sub-500 µm fractures.

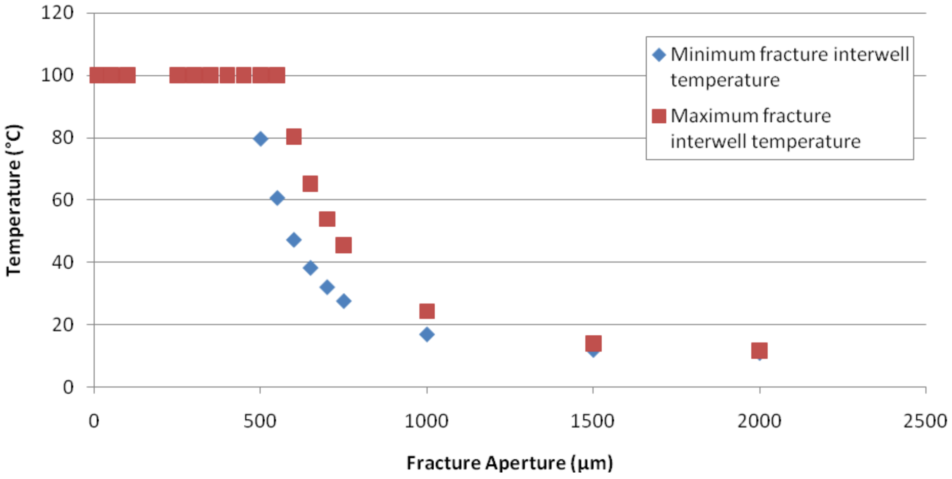

Figure 6: Summary of minimum and maximum interwell temperatures after one year of heating, showing the influence of fracture aperture.

Sensitivity to Rock Type

Compared to the hydrogeological parameters, host rock material properties play a relatively minor role in determining temperature distributions throughout the treatment zone. This behavior is not surprising, as the range of material properties is far smaller than the range of hydrogeological parameters. Heating in rocks with low thermal diffusivity will progress more slowly than in rocks with high thermal diffusivity; yet, this variation does little to affect the shape of the steady-state temperature profile. This behavior is exemplified in Figure 7, which shows early and late time behavior for heating in a shale, limestone, dolomite, and sandstone.

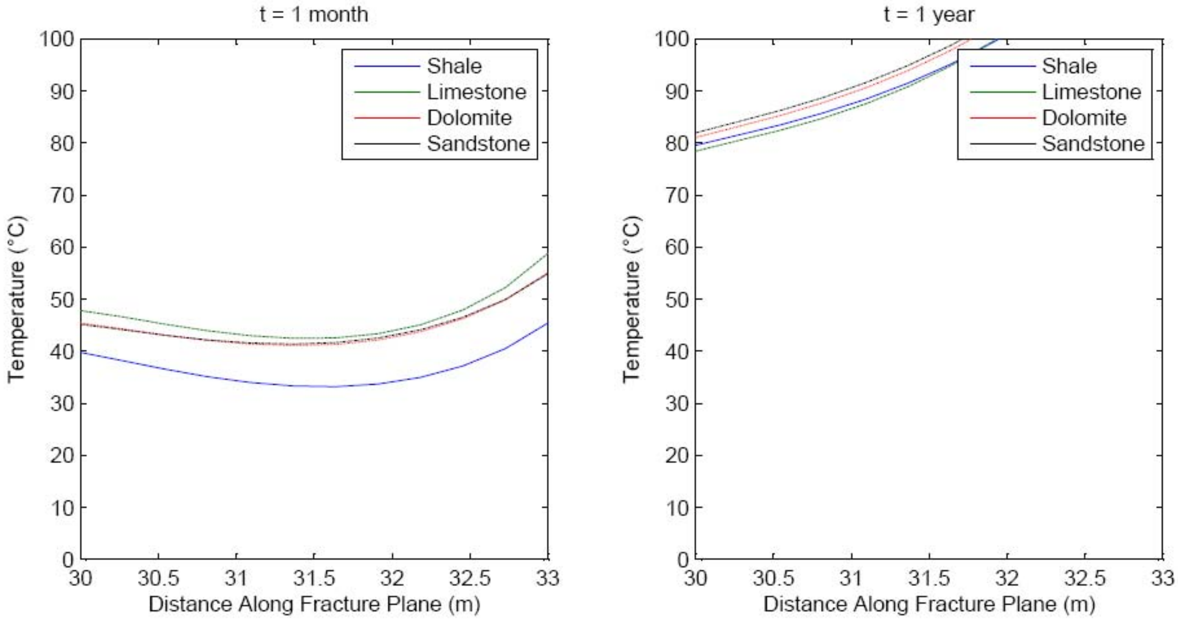

Figure 7: Early and late interwell fracture temperature profiles after one year of heating, as calculated for several rock types. Thermal properties for each rock type are presented in Table 1.

Mitigation

The semianalytical solution was also used to model two simple methods of overcoming the fracture cooling effect: the installation of a preheating well, and the augmentation of the thermal well heat production.

Boiling may be achieved despite fracture cooling simply by increasing the heat production in the thermal wells. Using the parameters from the base case, the time required to achieve boiling throughout the interwell zone is shown in Figure 8. At heat production rates below 130 W/m, boiling does not occur within 3 years. However, the time required for boiling decreases sharply above 130 W/m, bottoming out near one month for heat fluxes above 400 W/m. Because the total power consumption is strongly correlated to the time to boiling, it is advantageous to generate heat at the highest rate possible.

During field applications of TCH, power inputs in the range of 500 to 1,200 W/m have been used. This shows that the TCH technology should be able to cope with very significant groundwater flow in fractures. For practical applications where the location and abundance of fractures are seldom known, setting the heater well temperature by thermostat controls may be the easiest and simplest way to overcome cooling in fractures. Thermocouples situated near the heaters, or at select matrix loations, may provide the signal for the power controllers.

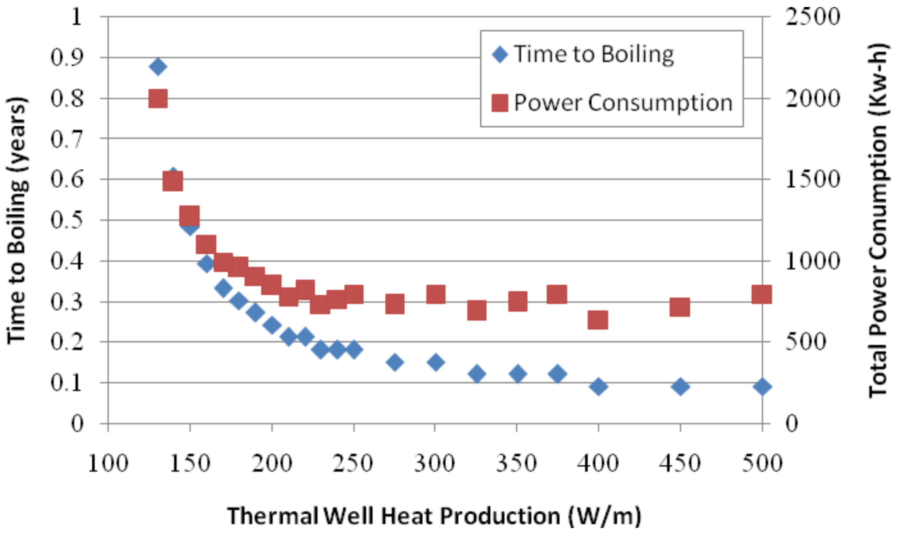

Figure 8: Effect of increased heat production rate on boiling time and total power consumption

Mitigation using an upgradient preheating well was also modeled. Again using the base case parameters, an additional well was placed 3 m upgradient of the first well, and the temperature in the original interwell zone was monitored through time. Although the preheating well caused a significant rise in the interwell temperatures, it was not sufficient to bring about boiling throughout this zone. Consequently, it would seem that installation of a preheater well would be appropriate only when heat production within the treatment zone could be increased no more due to limitations of the equipment.

Conclusions

Hydrogeological parameters (fracture aperture, fracture spacing, and hydraulic gradient) exert a significant influence on the heating of fractured rock using TCH. Material properties (density, thermal conductivity, heat capacity) do have a small effect on the early-time temperature distribution in the rock, but on the whole are less significant than the hydrogeological parameters. In part, this is simply because the range of material property values observed amongst rock types is small compared to the range of hydrogeological parameter values; all of the aforementioned material properties have a range of much less than an order of magnitude.

A general trend is observable from the variation in hydrogeological parameters. For each set of parameters, a steady-state temperature profile exists below which the fractures have little effect. When ground water influx is very small (due to tight or widely spaced fractures, shallow gradient, etc.) the cooling effect is negligible for sub-boiling temperatures. For a mid-level ground water influx, such as the base case in this study, the cooling effect is negligible until a temperature of about 50° C, where heating begins to lag before reaching a steady state. Very high ground water influxes, such as the cases of e = 2000 µm, H = 0.25 m, and *dh/dx* = -0.05 have such low threshold temperatures that a steady state is reached almost immediately, before a significant temperature rise occurs. An important limitation of this study is that only sub-boiling temperatures were considered. Future numerical modelling will show if this behaviour persists at very high temperatures.

The most effective solution to the problem of inflow cooling is to simply increase the power delivered to the thermal wells. Current field equipment has the capacity to inject at least twice the amount of power per unit length as was used in these simulations. In the case where this may not be done due to equipment limitations or other concerns, preheating wells installed outside of the treatment zone may be used to mitigate the cooling effects.

Acknowledgements

The authors would like to thank the Natural Sciences and Engineering Research Council (NSERC) for supporting this work through the form of a Discovery Grant. The financial contributions of Queen's University are also acknowledged.

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