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Numerical Simulation of Underground Electrical Signals Caused by Hydrofracturing Operations

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ABSTRACT

When fluids are injected at high pressure into geothermal wells to create and/or enlarge fractures in the reservoir and stimulate production, the resulting fluid leakage away from the fracture surface into the relatively impermeable country rock can cause detectable transient electrical signals (voltages) to propagate outward into the reservoir through the mechanism of electrokinetic coupling (or "self-potential"). If nearby observation wells are equipped with appropriate sensors, these signals may be characterized and reveal information concerning fracture geometry and other fracture properties that is otherwise unobtainable or ambiguous based on microseismic monitoring alone.

A new numerical simulator ("SPFRAC") has been developed to forward-calculate the electrical signals that will emanate from a fracture (or network of fractures) when pressurized in this manner. A representation of the fracture network as a collection of interconnected triangular planar elements is superimposed upon a conventional regular three-dimensional Cartesian computational grid describing the low-permeability country rock. The theoretical approach is presented, and the capabilities and limitations of the SPFRAC simulator are discussed. SPFRAC itself has been configured for operation on either a Windows PC or a Unix/Linux workstation, and is available through the United States Department of Energy.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) development projects involve the artificial stimulation of relatively impermeable high-temperature underground regions (at depths of 2-4 kilometers or more) to create sufficient permeability to permit underground fluid circulation, so that hot water can be withdrawn from production wells and used to generate electrical power. Usually, stimulation is accomplished by injecting water into a well at high pressure, enhancing permeability by the creation and propagation of fractures in the surrounding rock formations (a process known as "hydrofracturing"). Beyond just a *motivation*, low initial system permeability is also an essential *prerequisite* to hydrofracturing. If the formation permeability is too high, excessive fluid losses will preclude the buildup of sufficient pressure to rupture rock.

The principal barrier to EGS utilization for electricity generation is project economics. Costs for geothermal electricity obtained from conventional hydrothermal systems are just marginally competitive. Unless and until the costs of routinely and reliably creating and exploiting artificial subterranean fracture networks that can deliver useful quantities of hot fluid to production wells for long periods of time (years) are reduced to levels comparable to those of a conventional geothermal development project, EGS will be of little interest to the electrical power industry.

A significant obstacle to progress in projects of this general type is the difficulty of appraising the properties (geometry, fluid transmissivity, *etc.*) of the fracture(s) created/re-opened by injection. Sustainability of power production is critically dependent upon reservoir thermal sweep efficiency, which depends in turn on the geometry of the fracture network and its interconnections with the various production and injection wells used to circulate fluid underground. If no permeable connections are created between the wells, fluid flow will be too slow for practical utility. If the connections are too good, however (such as a production/injection well pair connected by a single very permeable fracture), production wellhead temperatures will decline rapidly. Unless the permeable fractures created by hydrofracturing can be accurately mapped, the cost of subsequent trial-and-error drilling to try to establish a suitable fluid circulation system is liable to dominate project economics and render EGS impractical.

2. MAPPING THE FRACTURE SYSTEM

Characterization of the underground fracture network presently relies virtually exclusively on microearthquake surveys (except at those points where fractures actually intersect boreholes and can be detected directly by downhole fluid-loss and televiewer logs). During the injection/hydrofracturing operation, as fractures are opened and extended, small seismic events will occur along the dislocation surface which can be detected by arrays of sensitive seismometers (usually buried at shallow depths and/or in neighboring shut-in observation wells). This approach has limited spatial precision, however (uncertainties are usually worse than 100 meters), and can only discern fracture zones that actually produce detectable signals during pressurization. Moreover, microseismic surveys cannot discriminate among fractures of varying degrees of fluid transmissivity.

In recent years, techniques have been devised to calculate the effects of subterranean geothermal reservoir evolution upon surface geophysical surveys, based on the results of conventional numerical reservoir simulation calculations for hydrothermal reservoirs (Pritchett *et. al*, 2000). If repeated surveys exhibit systematic temporal changes from one survey to the next that can be correlated with events taking place in the reservoir, additional constraints are provided for history-matching studies, resulting in more robust and reliable reservoir models (see, for example, Nakanishi et al, 2001; Pritchett and Garg, 2002; Pritchett and Garg, 2003). Of these methods, the SP ("self-potential") technique appears to be most appropriate for monitoring the growth of underground fractures in EGS

stimulation operations. Conventional earth-surface SP surveys will not be very helpful owing to the great depth and limited strength of the signals from hydrofracturing, but continuous downhole SP monitoring (using electrodes in nearby shut-in observation wells) could in principle sense the progress of the reservoir pressurization that results from stimulation operations (Telford *et. al*, 1990). If so, data of this type could be used to supplement microseismic data to more completely characterize the fracture system. Recent experiments in Japan using shallow wells have observed transient SP signals caused by relatively low-pressure injection into permeable formations (Ishido and Pritchett, 2003). EGS hydrofracturing in relatively impermeable rock will presumably produce electrical signals that are much more intense but also much deeper and that propagate more slowly through the earth.

A few years ago, a computational feasibility study using the STAR reservoir simulator (Pritchett, 1995) and the "SP postprocessor" (Ishido and Pritchett, 1999) demonstrated that the general concept is viable (Pritchett and Ishido, 2005a). Pressurization of a fracture will cause the propagation of intense SP signals through the reservoir, with amplitudes many times stronger than detection thresholds reaching distances of hundreds of meters from the fracture in just a few weeks. These promising results led us to begin a multi-year research program involving additional calculations and parameter studies (Pritchett and Ishido, 2005b). The parameter studies showed that the SP signals are sensitive to (and therefore diagnostic of) fracture size, location, orientation, and transmissivity. We also performed laboratory tests on rock samples to obtain typical pertinent parameter values and preliminary deployment design studies (Pritchett *et. al*, 2006), and developed new software to permit efficient simulation of the SP signals emanating from pressurized fractured rock (Pritchett, 2008).

In particular, as described below, a new simulator called "SPFRAC" has been developed, together with graphical postprocessors for the presentation of computed results and comparisons between results and field data. In SPFRAC (in contrast to the STAR system), a single simulator calculates both the hydraulic response and the resulting changes in subsurface electrical potential. Numerous simplifications (relative to the general-purpose formulation used in STAR) have been introduced, which have substantially reduced the computer time required to obtain useful results. These include restrictions to single-phase fluid flow, regarding temperature and fluid composition as functions of position only, certain geometric simplifications, and simplified constitutive relationships. But several generalizations have also been introduced to make SPFRAC better suited to address the hydrofracture/stimulation problem at hand, including more general treatment of the flow of fluid through fractured rock. This formulation is outlined in the next section.

3. CALCULATING ELECTRICAL POTENTIAL

Stable spatial distributions of electrical potential (voltage) are present naturally in the undisturbed earth, both at the ground surface and at depth. In geothermal areas, this "self-potential" (SP) can arise from as many as three different causes acting together: underground *temperature gradients* ("the earth as a thermocouple"), heterogeneities in subsurface formation *chemical composition* ("the earth as a battery"), and *electrokinetic effects* caused by fluid circulation through the rock ("the earth as a dynamo"). During geothermal field operation, however, temporal *changes* in the observed self-potential distribution will be dominated by electrokinetic effects, since the underground fluid flow pattern will change relatively rapidly with time as well flow rates change, compared to large-scale changes in system temperature or chemical composition (Ishido and Pritchett, 2000). Therefore, to interpret rapid changes in SP, it suffices to restrict our attention to electrokinetic phenomena.

3.1 Electrical Potential and Drag Current

It may easily be shown (Ishido and Pritchett, 1999) that the three-dimensional distribution of electrokinetic self-potential at an instant of time may be determined by solving a boundary-value problem given by Poisson's equation (derivable from Ohm's Law):

$$\nabla \cdot [\, \sigma \, \nabla V] \;=\; \nabla \cdot \boldsymbol{I}_{\mathbf{drag}} \qquad (1)$$

where V is electrical potential (volts), σ is electrical conductivity (siemens/meter), and $\boldsymbol{I}_{\mathbf{drag}}$ is the "drag current" density vector (amperes per square meter) induced by the flowing fluid. Therefore, if the spatial distributions of electrical conductivity (resistivity^{-1}) and drag current density are known at a particular instant of time, equation (1) can be solved to obtain the simultaneous distribution of electrical potential (V) everywhere underground.

To model the "drag current density" ($\boldsymbol{I}_{\mathbf{drag}}$), the formulation devised by Ishido and Mizutani (1981), which is based on extensive laboratory measurements on actual crustal rock samples of geothermal relevance, is adopted. Briefly, under single-phase fluid flow conditions this model expresses the drag current density as:

$$\boldsymbol{I}_{\mathbf{drag}} \;=\; -\,[(\varphi\, \varepsilon\, \zeta) / (\rho\, k\, \Theta^2)]\; \boldsymbol{M} \qquad (2)$$

where $\boldsymbol{M}$ is the local instantaneous liquid-phase mass flux vector (kilograms per second per square meter), ρ is the mass density of the liquid phase (kilograms per cubic meter), φ is the (dimensionless) system porosity, ε is the dielectric permittivity of the liquid phase (farads/meter), k is the absolute permeability of the rock (square meters), Θ is fluid-conduit tortuosity (dimensionless), and ζ is the adsorption potential or "zeta-potential" (volts). Calculation of these effects requires the functional dependence of various properties of the reservoir fluid upon quantities such as pressure, temperature and salinity.

The adsorption potential ζ in equation (2) is a function of temperature, and also depends upon acidity (*pH*) and the concentrations of *1:1*- and *2:2*-valent electrolyte in the liquid brine; it is given by equations 18, 20 and 21 of the above-cited paper by Ishido and Mizutani, assuming that the following empirical relationship holds for the distance (X_s) between the solid surface and the slipping plane in the electrical double layer:

$$X_s \text{ (meters)} = 3.4 \times 10^{-6}\, \mu \qquad (3)$$

where μ is the dynamic viscosity of the liquid phase in pascal-seconds. This formulation has been shown to yield good agreement with adsorption potential values measured in the laboratory for igneous and metamorphic rocks characteristic of geothermal systems (Tosha *et. al*, 2003).

Values for ζ are ordinarily negative; the magnitude tends to increase with increasing temperature, and is usually of the order of –100 millivolts at temperatures near 200°C for brine salinities in the 1000 ppm ("part per million") range for a variety of rock types. The adsorption potential magnitude tends to decline with increasing brine salinity, dropping to around –20 millivolts for 200°C seawater.

3.2 Darcy's Law

In the case of single-phase liquid flow in porous rock, the mass flux vector $\boldsymbol{M}$ is related to the fluid density (ρ), the rock permeability (k), the fluid dynamic viscosity (μ) and the gradient of "excess pressure" (p) by Darcy's Law:

$$\boldsymbol{M} = -(\rho\, k / \mu)\, \nabla p \tag{4}$$

and p, the "excess pressure" or "overpressure" (a function of position and time) is the difference between the actual local instantaneous pressure (P) and the local hydrostatic pressure (P_H):

$$p = P - P_H \tag{5}$$

and the hydrostatic pressure is:

$$P_H = P_o + (d - d_o)\, \rho\, g \tag{6}$$

where P_o represents a constant "average" pressure for the system (here taken as the undisturbed stable reservoir hydrostatic pressure at the fluid injection location), g is the acceleration of gravity (9.8 m/s^2), d is vertical depth, and d_o is the reference depth associated with P_o (*i.e.* the injection point depth).

3.3 The Streaming Potential Coefficient

In the special case of single-phase liquid flow through a system with uniform properties (conductivity, porosity, permeability, density, viscosity, salinity, temperature, tortuosity *etc.*), by incorporating Darcy's Law the above Poisson's equation (1) for the electrokinetic self-potential may be specialized to the following simple form:

$$\nabla^2 V = \xi\, \nabla^2 p \tag{7}$$

where ξ, the so-called "*streaming potential coefficient*", is a correlation coefficient between pressure disturbance (p) and local electrical potential disturbance (V) given by:

$$\xi = (\varphi\, \varepsilon\, \zeta) / (\sigma\, \mu\, \Theta^2) \tag{8}$$

As noted above, ζ is usually negative so $\xi < 0$ and regions of higher than average pressure (near a pressurized fracture, for example) will tend to be correlated with regions of negative electrokinetic potential anomaly. Although the uniformity assumptions implicit in equation (7) are too restrictive for the present purpose, the qualitative character of this correlation and the definition (equation 8) of the "*streaming potential coefficient*" ξ itself are key concepts behind the theoretical development underlying the SPFRAC simulator formulation.

3.4 Fluid Mass Conservation

To establish the fluid mass flux vector $\boldsymbol{M}$ (which depends on both location and time), the distribution of the fluid pressure (also dependent upon position and time) is required. For this purpose, the principle of fluid mass conservation is invoked and can be written:

$$\partial(\varphi\rho) / \partial t + \nabla\cdot\boldsymbol{M} = \textit{source terms} \tag{9}$$

or, using Darcy's law,

$$\partial(\varphi\rho) / \partial t = \nabla\cdot[(\rho\, k / \mu)\, \nabla p\,] + \textit{source terms} \tag{10}$$

where, again, φ = porosity, ρ = fluid density, k = permeability, μ = fluid viscosity, and p = excess pressure or "overpressure". The "*source terms*", for the present application, represent the effects of the operation of wells (positive for injection and negative for production). The left-hand side of the above mass balance equation (10) may be decomposed to:

$$\begin{aligned}\partial(\varphi\rho) / \partial t &= \varphi \times (\partial\rho / \partial t) + \rho \times (\partial\varphi / \partial t) \\ &= (\varphi\,\rho) \times (C_w + C_r) \times (\partial p / \partial t)\end{aligned} \tag{11}$$

where C_w and C_r are the isothermal "water compressibility" and "rock compressibility" respectively, and are given by:

$$C_w = (\partial\rho / \partial p) / \rho \tag{12}$$

$$C_r = (\partial\varphi / \partial p) / \varphi \tag{13}$$

and the partial derivatives are evaluated at constant temperature. The rock compressibility C_r will in general be a function of position. The fluid compressibility C_w may be regarded as a function of temperature and salinity for single-phase liquid flow, and since both temperature and salinity are regarded as functions of position only in the present formulation, the total compressibility:

$$C = C_w + C_r \tag{14}$$

is also a function of position only (like ρ, μ and φ). Thus, we may finally write the above mass balance equation (10) as a diffusion equation for the fluid overpressure:

$$(\varphi\rho C) \times (\partial p / \partial t) = \nabla\cdot[(\rho\, k / \mu)\, \nabla p\,] + [\textit{source terms}]_m \tag{15}$$

and the expression for the electrical potential V may now be written:

$$\nabla\cdot[\,\sigma\, \nabla V\,] = \nabla\cdot[\,\sigma\, \xi\, \nabla p\,] + [\textit{source terms}]_e \tag{16}$$

3.5 Solution Technique

In equations (15) and (16) the quantities φ (rock porosity), C (total compressibility), ρ (fluid density), μ (fluid viscosity), σ (electrical conductivity) and ξ (streaming potential coefficient) are regarded as known functions of position alone. The principal unknowns (functions of position and time) are the fluid overpressure (p) and the electrical potential (V). The rock permeability (k) is also a function of position and time which depends on the fluid overpressure p. The "source terms" in equations (15) and (16) arise from the presence of wells penetrating the region. In equation (15), "$[\textit{source terms}]_m$" represents the effects of fluid injection or withdrawal from the wells upon the distribution of fluid mass (and pressure). In equation (16), "$[\textit{source terms}]_e$" represents the electrical effects of buried conductive metallic well casings upon the distribution of electrical potential in the formation. These are discussed at length below.

The SPFRAC simulator uses a fully implicit finite-difference technique to solve the above system of equations (15 and 16) in a three-dimensional volume of space shaped like a rectangular prism subdivided into numerous "grid blocks". The computing volume is large, and extends far beyond the fractured region influenced by hydrofracturing. Usually, this fractured region (and the feedzone of the injection well used to stimulate the system) will be centrally located within the computing volume. At large distances (*i.e.* at the outer perimeter of the computing volume), both the fluid overpressure p and the electrical potential V are taken to be equal to zero for all times t. The grid blocks adjacent to the grid boundaries will usually be much larger in size than those in the central region. The user assigns the

dimensions of the various grid blocks; each block *(i, j, k)* will have a volume given by $\Delta v_{ijk} = \Delta x_i \times \Delta y_j \times \Delta z_k$.

Initially, both p and V are taken to be zero everywhere. Then, the solution is advanced in time by *(1)* solving (15) to find the distribution of fluid overpressure p after a short time interval (Δt), and then *(2)* solving (16) to determine the corresponding spatial distribution of electrical potential V at the same time. The process is then repeated to obtain pressures and potentials at a subsequent time level, and so on. In this way, the space/time distributions of p and V are calculated, step-by-step. Note that in equations (15) and (16) the distribution of electrical potential V depends on the pressure (p) distribution, but the pressure distribution itself is independent of V. This means that it is not necessary to recalculate the potential distribution (using equation 16) each and every time that the pressure distribution is updated – electrical potential only needs to be recomputed when it is required for comparisons with field measurements.

3.6 Modeling Fracture Permeability

Using SPFRAC, the rock permeability is regarded as the sum of *(1)* the "matrix" permeability k_m (which is small but nonzero in all of the blocks of the grid and is invariant with time), and *(2)* the "fracture" permeability k_f, which is non-zero in only a small fraction of the computational grid blocks, but which depends in general on time:

$$k\,(\boldsymbol{r},t) \;=\; k_m\,(\boldsymbol{r}) \;+\; k_f\,(\boldsymbol{r},t) \qquad (17)$$

The "matrix permeability" k_m is user-assigned, but the "fracture permeability" k_f is calculated within SPFRAC using an "equivalent hydraulic aperture" approach.

Consider a single planar smooth-walled rock fracture characterized by a particular value of "aperture" λ (the distance between the parallel rock faces bounding the fracture). It is easy to show that under conditions of steady laminar viscous liquid flow, the average fluid velocity in the fracture subject to a pressure gradient ∇p along the fracture will be given by:

$$\boldsymbol{u_{avg}} \;=\; -\,(\nabla p\,/\,\mu)\;\times\;(\lambda^2\,/\,12) \qquad (18)$$

If we consider an element of such a fracture (of area a) embedded within a volume of rock of total volume v, it follows (invoking Darcy's Law) that the average additional "fracture permeability" contributed to the volume by the presence of the fracture will be given by:

$$\Delta k_f \;=\; (a\,/\,v)\;\times\;(\lambda^3\,/\,12) \qquad (19)$$

and the "fracture transmissivity" (or the "*kH product*") is:

$$\text{"}kH\text{"} \;=\; \lambda^3\,/\,12 \qquad (20)$$

So, for a particular computational grid block (with $v = \Delta v_{ijk}$), the "fracture permeability" will simply be the total of the Δk_f's contributed by the various fractures that pass through the block.

Equation (19) describes how to calculate the "fracture permeability" due to a fracture of "equivalent hydraulic aperture" λ, but λ itself remains to be determined. For each fracture present, it is assumed that some initial aperture value λ_o prevails at $t = 0$ over the entire fracture surface. Thereafter, the aperture at each point along the fracture surface will change with time according to:

$$\partial\lambda\,/\,\partial t \;=\; B\;\times\;\partial p\,/\,\partial t \qquad (21)$$

where in general the coefficient B for any particular fracture may take on one of two values (B_i or B_d) at any particular time:

$$B \;=\; B_i \quad \text{if } \partial p\,/\,\partial t > 0 \;\; \underline{\text{and}} \;\; p = p_{max}$$
$$B \;=\; B_d \quad \text{if } \partial p\,/\,\partial t \le 0 \;\; \underline{\text{or}} \;\; p < p_{max} \qquad (22)$$

where p_{max} means "the highest value of p experienced so far at this location," and where it is required that $B_d \le B_i$. Each fracture may have individual (B_i, B_d, λ_o) parameter values.

This model (equations 19 – 22) provides substantial flexibility in prescribing the time-history of "fracture permeability" for a particular fracture. For example first consider the simplest case where $\lambda_o = 0$ and where $B_d = B_i$. Let us consider five temporally successive states (at $t = t_1$, t_2, t_3, t_4 and t_5), with the local fluid overpressure being zero, $p_{inj}/2$, p_{inj}, $p_{inj}/2$ and zero in that order (that is, fracture pressurization followed by subsequent depressurization). The corresponding values of the fracture aperture and of the fracture transmissivity will be:

Time t	Pressure p	Aperture λ	Transmissivity kH
t_1	0	0	0
t_2	$p_{inj}/2$	$B_i \times p_{inj}/2$	$(B_i \times p_{inj})^3/96$
t_3	p_{inj}	$B_i \times p_{inj}$	$(B_i \times p_{inj})^3/12$
t_4	$p_{inj}/2$	$B_i \times p_{inj}/2$	$(B_i \times p_{inj})^3/96$
t_5	0	0	0

Next, consider a similar situation but where $B_d = (B_i / 2)$. In that case, the corresponding results will be:

Time t	Pressure p	Aperture λ	Transmissivity kH
t_1	0	0	0
t_2	$p_{inj}/2$	$B_i \times p_{inj}/2$	$(B_i \times p_{inj})^3/96$
t_3	p_{inj}	$B_i \times p_{inj}$	$(B_i \times p_{inj})^3/12$
t_4	$p_{inj}/2$	$B_i \times p_{inj} \times (3/4)$	$(B_i \times p_{inj})^3 \times (9/256)$
t_5	0	$B_i \times p_{inj}/2$	$(B_i \times p_{inj})^3/96$

which describes a fracture exhibiting permanent deformation, with finite residual transmissivity remaining even after pressurization is over. Finally, consider the effect of specifying non-zero values for the initial effective aperture λ_o. If $\lambda_o > 0$, then the fracture will already be somewhat permeable before stimulation begins, and pressurization will have the effect of further increasing the fracture transmissivity. If on the other hand $\lambda_o < 0$ is specified, SPFRAC treats the fracture permeability as zero for negative λ values, which means that the fracture will not actually begin to open physically until the local overpressure reaches a finite "threshold" given by:

$$p^* \;=\; -\,\lambda_o\,/\,B_i \qquad (23)$$

3.7 Representing the Injection Well

The effects of fluid injection are of central importance to the EGS reservoir stimulation problem, and are reflected in the SPFRAC simulator through the "[*source terms*]$_m$" in equation (15) above. For most of the blocks in the computational grid "[*source terms*]$_m$" will be zero, but at least one grid block will contain the "feedpoint" of the injection well where fluid mass is added to the grid volume as time goes on. SPFRAC also allows for a "feedzone" of finite vertical extent, involving multiple vertically-adjacent grid blocks and the simultaneous stimulation of multiple fracture systems. Also note that, although there is no particular requirement that the injection well feedzone intersects a fracture, calculations in which this is not the case are likely to be of little practical interest for EGS.

We consider the "feedzone" to consist of a vertical circular cylinder of finite height, with a diameter equal to the wellbore diameter (and ordinarily much smaller than the grid block dimensions). Injection may be specified by identifying the "feedblock(s)" involved and either prescribing a volumetric flow rate history or an injection pressure history (or a combination, with pressure specified for part of the history and flow specified for the remainder). In either event, the objective is to uniquely establish the time-variation of the injection/backflow rate.

The relationships in the feedblock(s) among the well radius r_{well}, the horizontal permeability in the feedblock k_h, the fluid viscosity in the feedblock μ_{ijk}, the vertical length of the open (*i.e.* uncased) section lying within the feedblock Λ_{ijk}, the injection well's dimensionless "skin factor" s_{well}, the instantaneous overpressure within the injection well p_{well}, the instantaneous grid block pressure p_{ijk} and the volumetric flow rate of fluid from the injection well into the formation in the grid block R (*i.e.* cubic meters per second) are given by:

$$R = 2\,\pi\,\Lambda_{ijk}\,k_h\,(p_{well} - p_{ijk}) \;/\; \{\,\mu_{ijk} \times [\,\log_e(r_{eff}/r_{well}) + s_{well}\,]\,\} \qquad (24)$$

where r_{eff} is the so-called "effective well-block radius" which is proportional to the size of the feedblock itself. Rules for determining r_{eff} are well-established (see Pritchett and Garg, 1980; also see Appendix B of Pritchett, 2002). In the special case of a uniform grid with a square wellblock ($\Delta x = \Delta y$), the effective wellblock radius will be given by $r_{eff} = 0.1985 \times \Delta x$. Procedures for automatically estimating r_{eff} under more general circumstances are incorporated within the SPFRAC simulator.

3.8 Effects of Metallic Well Casings

As noted by Pritchett and Ishido (2005b), the presence of electrically conductive steel well casing pipe within the reservoir can perturb the electrical signals propagating outward from the pressurized fractures. To minimize such effects, Pritchett *et al.* (2006) recommended the use of non-metallic casing materials for the observation wells, at least at depths comparable to the fracture system depth. But these recommendations may not always be followed, and moreover material strength considerations will probably require the use of steel casing in the injection well, which means that the electrical potential distribution is likely to be perturbed near that well by electric currents flowing vertically in the pipe.

Since the electrical conductivity of steel (of order 10^7 S/m, depending somewhat on the alloy characteristics and on temperature) exceeds underground formation conductivity values typically encountered in geothermal reservoirs by between eight and ten orders of magnitude, it suffices to regard these structures as infinitely conductive, so that at any instant of time the electrical potential along the pipe will be uniform, and the potential in the reservoir formation immediately adjacent to the pipe will be likewise the same everywhere along its surface. Electric currents will flow longitudinally in the metal pipe to equalize the potentials along its length, and the net electric current will be exactly zero, with electrons flowing outward from the pipe to the formation and inward from the formation to the pipe in equal numbers. Thus, for any particular continuous metallic conductor, the electrical potential will be at most a function of time.

SPFRAC considers two cases. In the first, the cylindrical conductor is very long and extends outward through the boundary of the computational volume (often all the way to the earth surface). In this case, it is assumed that the electrical potential on the conductor is simply equal to zero (the imposed "distant" boundary value).

If, however, the cylindrical conductor is entirely contained within the study volume, it is assumed that the potential on the conductor, although uniform along its length, will "float" and vary with time. Consequently, in the latter case a procedure for establishing the potential on the conductor at each instant of time is required.

The effects of electric currents flowing through these buried metal pipes and between the pipes and the surrounding geological formations are taken into account using the $[source\ terms]_e$ in equation (16). For any particular computational grid block (i, j, k) containing a metal pipe, it is easy to show that the electric current (amperes) flowing from the pipe surface into the formation within the grid block volume is given by:

$$I_{ijk}\,(\text{amperes}) = 2\,\pi\,L_{ijk}\,\sigma_{ijk}\,(V_{case} - V_{ijk}) \;/\; \log_e(r_{eff}/r_{case})_{ijk} \qquad (25)$$

where L_{ijk} is the portion of the pipe length (in meters) that passes through grid block (i,j,k), σ_{ijk} is the electrical conductivity of the grid block (siemens/meter), V_{case} is the uniform instantaneous electrical potential along the pipe (volts), V_{ijk} is the instantaneous grid block potential (volts), r_{case} is the radius of the steel casing (*i.e.* the well radius, in meters) and r_{eff} (meters) is again the "effective well-block radius" calculated in exactly the same way as outlined above in section 3.7.

If the conductor is "grounded" (that is, the pipe extends beyond the computational grid volume and is therefore at zero potential), then $V_{case} = 0$ and equation (25) may be summed over all of the grid blocks containing the pipe to establish the total electric current flowing through the outer boundary into the computing volume through this particular conductor:

$$I_{total}\,(\text{amperes}) = -2\,\pi \sum [L\,\sigma\,V / \log_e(r_{eff}/r_{case})]_{ijk} \qquad (26)$$

If on the other hand the conductor is "floating" (entirely contained within the computing volume), the electrical potential on the conductor at each instant of time may be established by the requirement that the net current in/out of the conductor as a whole must be zero, so:

$$V_{case} = \sum (W_{ijk} \times V_{ijk}) \;/\; \sum W_{ijk} \qquad (27)$$

where the grid block (i,j,k) weighting factor W_{ijk} is given by:

$$W_{ijk} = [\,L_{ijk} \times \sigma_{ijk}\,] \,/\, [\,\log_e(r_{eff}/r_{case})\,]_{ijk} \qquad (28)$$

3.9 Constitutive Relations

SPFRAC considers the native reservoir fluid to consist of aqueous liquid sodium chloride (NaCl) brine. The user specifies spatial distributions of temperature T and brine salinity S (mass fraction of dissolved NaCl in the fluid), and the distributions of other several pertinent properties are then automatically computed by the simulator using mathematical fits to handbook values for the properties of such brines. These quantities include the fluid density ρ, the fluid compressibility C_w, the fluid viscosity μ, the fluid electrical conductivity σ_w, and the fluid's absolute dielectric permittivity ε.

4. SOFTWARE AND DOCUMENTATION

The SPFRAC software consists of *(1)* the simulator itself and *(2*) nine additional programs that are suitable for preparing various types of graphical output to represent the computed results and to compare them with measurements. Contour-plots of either pressure disturbance (*p*) or electrical potential (*V*) may be displayed in arbitrarily-oriented planes at fixed instants of time. The injection history (injection pressure, injection flow rate and cumulative injection as functions of time) may also be displayed. Time-history plots of both pressure disturbance (*p*) and electrical potential (*V*) at fixed spatial locations are also available.

Both the SPFRAC software and documentation (a "User's Manual" is provided by Pritchett, 2008) may be obtained through the United States Department of Energy. Suitable program configurations are available for operation either on a Microsoft Windows PC or on a Unix/Linux scientific workstation. The manual provides detailed instructions for the preparation of files containing input data for processing by SPFRAC. These input data include problem geometry (discretization, fracture system geometry, well and casing geometries), the spatial distributions of key parameters (including temperature *T*, salinity *S*, rock porosity φ and compressibility C_r, country rock matrix permeability k_m and tortuosity Θ, electrical conductivity σ, adsorption potential ζ or streaming potential coefficient ξ), the characteristics of each fracture (B_i, B_d, and λ_o), and the fluid injection history. If available, the user may also provide measured field data for comparison with the computed results.

5. CONCLUSIONS

A new simulator suitable for forward-calculating the space-time distribution of underground electrokinetic potential anomaly signals caused by hydrofracture pressurization has been developed. The simulator has been extensively tested using synthetic input data and has proven both efficient and accurate. Computational examples are provided by Pritchett (2008). SPFRAC is now complete and available for use by the geothermal community. The next step would appear to be to perform field-scale experiments along these general lines and then to attempt to interpret the results using SPFRAC. We hope that such results will be ready to report in time for World Geothermal Congress 2015.

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