Application of Self-Potential Measurements to Reservoir Engineering

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A computational tool so called the “EKP-postprocessor” has been developed to calculate space/time distributions of self-potentials caused by electrokinetic coupling resulting from histories of underground conditions (pressure, temperature, vapor saturation, concentration of dissolved species, etc.) computed by unsteady multi-dimensional geothermal reservoir simulations (Ishido and Pritchett, 1999). This forward calculation technique enables us to incorporate self-potential monitoring data into history-matching studies to improve mathematical reservoir models. In addition to history-matching studies, the EKP-postprocessor can be applied to various problems related to subsurface fluid flow in volcanic areas, sedimentary basins, etc. and characterization of the transport properties of reservoir-forming rocks. In this paper, the results of numerical simulation studies using the EKP-postprocessor to appraise the utility of a combination of pressure and self-potential transient data to characterize fractured reservoirs are presented.

1. INTRODUCTION

In recent years the self-potential method has attracted increasing interest in the detection and characterization of groundwater flow, since subsurface fluid flow generates self-potential (SP) anomalies at the ground surface through electrokinetic coupling. Changes in SP are also expected to appear associated with pumping or injection operations both in phreatic and confined aquifers.

Ishido and Pritchett^{1),2)} have developed a computational tool so called the “EKP-postprocessor” to calculate time-dependent distributions of SP from changing underground conditions as computed by unsteady multi-phase multi-component reservoir simulations. This forward calculation technique enables us to incorporate SP monitoring data into modeling procedures to improve any proposed mathematical reservoir models. Because uncertainty in predictions of numerical reservoir models is directly related to the amount of field data available against which the models can be tested, it is clear that the addition of SP monitoring data to the list of pertinent field measurements is likely to improve the reliability of these forecasts.

In addition to geothermal reservoir engineering, the EKP-postprocessor has been applied to volcano studies to understand SP generation and its changes around summit craters³⁾, feasibility studies of SP measurements for CO₂ geological storage

monitoring⁴⁾ and so on.

In the present paper, an outline of the EKP-postprocessor is described, and then the results of EKP-postprocessor calculations to study the possibility of characterizing fractured reservoirs using a combination of pressure and SP transient data are presented.

2. EKP-POSTPROCESSOR

(1) Electrokinetic coupling

The flow of a fluid through a porous medium will generate an electrical potential gradient (called the electrokinetic or streaming potential) along the flow path by the interaction of the moving pore fluid with the electrical double layer at the pore surface. This process is known as electrokinetic coupling. The general relations between the electric current density **I** and fluid volume flux **J**, and the electric potential gradient $\nabla\phi$ and pore pressure gradient $(\nabla P - \rho g)$ forces are

$$\mathbf{I} = -L_{ee} \nabla\phi - L_{ev} (\nabla P - \rho g) \quad (1)$$

$$\mathbf{J} = -L_{ve} \nabla\phi - L_{vv} (\nabla P - \rho g) \quad (2)$$

where the L_{ij} are phenomenological coefficients⁵⁾. The first term on the right-hand side in (1) represents Ohm's law and the second term in (2) represents Darcy's law. The cross-coupling terms (with the L_{ev} and L_{ve} coefficients) represent the

electrokinetic effect; $L_{ev} = L_{ve}$ according to Onsager's reciprocal relations.

Based upon a capillary model, the above coefficients may be written as follows^{2),5)}:

$$L_{ev} = -\eta \varepsilon \zeta R_{ev} G / \tau \mu \quad (3)$$

$$L_{ee} = \eta (\sigma + m^{-1} \Sigma_s) / \tau \quad (4)$$

where:

- η : porosity,
- ε : liquid-phase dielectric permittivity,
- ζ : zeta-potential,
- R_{ev} : “electrical relative permeability” for two-phase flow,
- G : correction factor which becomes less than unity only if the hydraulic radius is comparable to the thickness of the electrical double layer,
- τ : square of tortuosity ($\tau = t^2$),
- μ : liquid-phase viscosity,
- σ : electrical conductivity of pore fluid,
- m : hydraulic radius of pores and/or cracks ($m = \eta S^{-1}$, S : specific internal surface area),
- Σ_s : surface conductance.

Equation (1) describes the total current density, composed of a drag (convection) current density I_{drag} caused by charges moved by fluid flow, and a conduction current density I_{cond} caused by electric conduction; hence,

$$I = I_{cond} + I_{drag} \quad (5)$$

where

$$I_{cond} = -L_{ee} \nabla \phi$$

$$I_{drag} = -L_{ev} (\nabla P - \rho g)$$

In the absence of external current sources, $\nabla \cdot I = 0$, so from (5):

$$\nabla \cdot I_{cond} = -\nabla \cdot I_{drag} \quad (6)$$

Equation (6) represents sources of conduction current that are required for the appearance of electrical potential.

In a homogeneous region, (6) can be written as:

$$\nabla^2 \phi = C \nabla^2 (P - \rho g z) \quad (7)$$

where C is called the streaming potential coefficient:

$$C = -L_{ev} / L_{ee} = \varepsilon \zeta / (\sigma + m^{-1} \Sigma_s) \mu \quad (8)$$

If the pore pressure change occurs within a finite homogeneous volume, the following relation between changes in ϕ (streaming potential) and $(P - \rho g z)$ (pressure) prevails:

$$\Delta \phi = C \Delta (P - \rho g z) \quad (9)$$

The cross-coupling term in (2) may be safely neglected for typical geologic situations, and Darcy's law alone may be used to model the hydraulic problem; it is not necessary to solve (1) and (2) simultaneously. A “postprocessor” may then be used to calculate the drag current (I_{drag}) from the results of an unsteady thermohydraulic reservoir simulation.

(2) Outline of the EKP-postprocessor

The “EKP-postprocessor”²⁾ simulates electric potentials caused by subsurface fluid flow by a two-step process. First, it calculates the distribution of L_{ev} , L_{ee} and I_{drag} from the reservoir-simulation results using the same spatial grid used for the reservoir simulation calculation (called the RSV-grid hereafter). Next, the postprocessor calculates the electric potential (ϕ) distribution by solving the above Poisson equation (6) within a finite-difference grid that is usually much greater in spatial extent than the RSV-grid (hereafter called the SP-grid).

Within that portion of the SP-grid overlapped by the RSV-grid, the distribution of electrical conductivity is obtained directly from RSV-grid values. Elsewhere within the SP-grid, the electrical conductivity distribution is user-specified and time-invariant. Ordinarily, boundary conditions on the potential are: zero normal gradients (Neumann condition) on the ground surface (upper surface) and zero potential (Dirichlet condition) along the bottom and vertical sides of the SP-grid. To calculate the grid-block-face drag current density within the RSV-grid, η , τ , ε , G and ζ in (3) are computed at grid block interfaces using harmonic means. Other interface quantities in (3) are treated using a second-order upstream weighting scheme. Equation (6) is solved numerically using a Gauss-Seidel iteration procedure incorporating intermittent automatic optimization of the overrelaxation factor.

The EKP-postprocessor was originally developed as one of the mathematical postprocessors for the “STAR” code⁶. The reservoir-simulation results required for postprocessor calculations are stored on the so-called “GEO” output file.

Ishido and Pritchett⁷ extended the EKP-postprocessor so as to calculate the drag current density in “MINC” media⁸. In the MINC representation, the contribution of mass exchange through the matrix region is neglected in mass exchange between adjacent macroscopic computational grid blocks. However, the contribution through the matrix region is not negligible for the drag current density. This is because the magnitude of the drag current is not proportional to the permeability, but to the porosity. The contribution of the matrix region is small at early times, but usually predominates under steady-state conditions.

3. FRACTURED RESERVOIR CHARACTERIZATION

(1) Pressure and SP transients in MINC media

Ishido and Pritchett⁷ performed a pressure-transient simulation for a two-dimensional axi-symmetric horizontal reservoir model. The formation is represented by a “MINC” double-porosity medium with the following properties:

- global permeability: $k = 10^{-14} \text{ m}^2$,
- fracture zone volume fraction: $\psi = 0.1$,
- fracture zone porosity: $\eta_f = 0.1$,
- matrix region porosity: $\eta_m = 0.1$,
- matrix region permeability: $k_m = 10^{-17} \text{ m}^2$,
- fracture spacing: $\lambda = 10 \text{ m}$.

The time required ($\tau_{pe} = \eta_m \mu C \lambda^2 / 10 k_m$) for pressure equilibration between the fracture and matrix regions is $\sim 10^4$ sec. The initial thermodynamic state is uniform (temperature = 200°C and pressure = 10 MPa). For the corresponding SP calculations, the reservoir fluid’s NaCl concentration is assumed to be 0.02 mol/L, and the formation conductivity L_{ee} is constant at 0.03 S/m.

Figure 1 shows semi-log plots of changes in pressure and in SP due to continuous injection at 0.5 tons per hour per meter of reservoir thickness. The pressure transient at a point near the injection well shows behavior typical of a double-porosity medium: the late-time slope develops after the time required for pressure equilibrium within the matrix region τ_{pe} has elapsed. The SP transient also exhibits three segments.

The drag current contribution through the matrix region is small at early times, so the slope is smaller

than that at late times, by the factor ψ ($= 0.1$). At intermediate times, SP changes rapidly with increasing involvement of matrix region. The time τ_{pe} can be clearly identified at the intersection of the intermediate-time and late-time semi-log straight lines. (In Figure 1, the “observation” point is not located within the borehole, but ~ 5 meters away from the injection well. The reason for this is that in the case of “open hole” the SP change within the borehole does not show the typical behavior like that shown in Figure 1 since the pressure in the matrix region coincides with the borehole pressure even in early times as approaching the borehole.)

Figure 1 Changes in pressure and SP at a point ~ 5 m away from the injection well (open hole) during injection test for fractured medium⁷. The pressure change for the equivalent porous medium is shown by broken curve.

Figure 2 Plot of the ratio of SP change to pressure change for the “double-porosity” and “equivalent porous medium” results.

Figure 2 shows the ratio of SP changes to pressure changes for the results shown in **Figure 1**. In the case of the equivalent porous medium, relationship (9) is satisfied for the entire period, resulting in an almost constant ratio. In this plot, the differences between double-porosity and equivalent porous medium behavior is much more apparent and the time τ_{pe} is more evident than in a plot of SP change itself (**Figure 1**). The change-ratio plot has the additional advantage that, in real situations, pressure transient data suffer from fluctuations in the sandface flow-rate, so it is often difficult to discern the three segments such as those shown in **Figure 1**. By contrast, the ratio of SP-change to pressure-change is insensitive to flow-rate fluctuations, so a combination of pressure and SP measurements is expected to provide a more robust and reliable technique for fractured reservoir characterization.

(2) Near-field effects

In the calculations described in the previous section, Ishido and Pritchett⁷⁾ did not consider the “near-field” effects around a borehole. Ishido et al.⁹⁾ constructed a reservoir model to treat a borehole and individual fractures explicitly instead of using the MINC double-porosity representation (**Figure 3**). The model is axi-symmetric, eight meters thick, and of 1 km horizontal extent (radius). Five equally-spaced horizontal fractures intersect the borehole located along the axis of symmetry. Sufficiently fine block spacing was adopted near the borehole (radius of 0.075 meter) to represent the well casing. Fine block spacing was also used for the host rock (matrix) region close to the fracture zone so as to resolve the high electrical potential gradients there.

The formation properties are:

fracture zone permeability: $k = 10^{-12} \text{ m}^2$,

fracture zone thickness = 0.01 m,

fracture zone porosity: $\eta_f = 0.5$,

host rock porosity: $\eta_m = 0.01$,

host rock permeability: $k_m = 10^{-18} \text{ m}^2$,

fracture spacing: $\lambda = 1 \text{ m}$.

The time required (τ_{pe}) for pressure equilibration between the fracture and matrix regions is $\sim 500 \text{ sec}$. The initial thermodynamic state is uniform (temperature = 45°C and pressure = 10 MPa). Fluid production takes place from the borehole with a constant pressure drawdown of 1 MPa.

For the corresponding SP calculations, the reservoir fluid's NaCl concentration is assumed to be 0.005 mol/L, and the streaming potential coefficient is uniform throughout the fracture and host rock regions.

In the “open hole” cases, the SP change that

would be measured by electrode(s) installed within the borehole (**Figure 3**) is calculated, and then the ratio of SP change to pressure change is plotted as a function of time (**Figure 4**). As **Figure 4** shows, the “open” ratio is almost constant with time, which is similar to the “equivalent porous medium” behavior shown in **Figure 2**, and does not exhibit any characteristic fractured reservoir behavior.

But if a skin zone in which the streaming potential coefficient is much smaller than that of the outer matrix region is present, the typical double-porosity behavior appears in the plot (“open (skin)” curves in **Figure 4**). Although the SP change magnitude is independent of the location of the electrode for the case without a skin zone, the SP change is slightly smaller at the electrode located at the matrix region for the case with skin zone as shown by the broken line in **Figure 4**.

In **Figure 4**, also shown is the result for a case in which the reservoir is represented by “equivalent” MINC double-porosity medium. In this “open (MINC)” case, the SP/pressure change ratio is almost constant with time (as mentioned in the previous section).

Figure 3 Conceptual model used to study “near-field” effects around a borehole. In cases of open hole (interval), SP signal is measured with electrodes deployed on a wireline.

Next we consider cased wells, in which the hydraulic communication between the borehole and the formation is restricted to the fracture region. Direct hydraulic contact between the borehole and matrix region is prevented by solid casing and cementing.

Figure 4 The ratio of SP change to pressure change as a function of time for “open hole” cases. The ratio’s for the case with a skin zone are labeled “open (skin)”, and the ratio calculated for MINC representation is labeled “open (MINC)”.

Figure 5 The ratio of SP change to pressure change as a function of time for “cased well” cases. (The ratio labeled “open” is the same as that shown in Fig. 4.)

If the casing pipe consists of a material that is not electrically conductive, SP will be measured using small electrodes installed outside the casing. Electrode response depends in this case on whether the electrode is situated in the fracture zone or in the matrix region. The normalized SP change is nearly constant near the fractures, but in the matrix region it is small at early times and rapidly increases as time approaches τ_{pe} , reflecting the pressure change in the matrix region (**Figure 5**).

If the casing material is conductive as in the more typical case of metallic casing pipe, the potential of the casing itself is measured. The normalized SP change is indicated by the curve labeled “conductive” in **Figure 5**, and represents an averaged behavior of the matrix and fractured regions.

(3) Observations at the Kamaishi Mine

At the Kamaishi Mine, Nishi et al.¹⁰⁾ carried out pressure and SP measurements in two open holes (KF-1 and KF-3) which are drilled nearly horizontally from the wall of one of the tunnels into the surrounding granodiorite body. Both wells maintain stable pressures of about five bars under shut-in conditions, so that flow tests may be carried out by simply opening and closing the wellhead valves. After preliminary experiments¹¹⁾ in 2005 and 2006, twelve silver-silver chloride electrodes were installed in each of the two wells in 2007.

In plots of the ratio of SP change to pressure change, very reproducible behavior which depended upon whether or not the electrode was located adjacent to a fracture, was observed. This ratio is almost constant after 100 seconds for electrodes located in the relatively impermeable country rock zone, but exhibits double porosity behavior near the fractures, which can be explained by the “open hole with skin” model behavior discussed in the preceding section.

This double porosity behavior is particularly evident in the results from the KF-1 electrodes. Based on the observed τ_{pe} value (~1000 seconds) and the matrix rock permeability (several microdarcies) deduced by testing core samples, we may estimate the fracture spacing to be a few meters. This is in good agreement with the value inferred from detailed geological observations.

The ratio of SP disturbance to pressure disturbance corresponds to the streaming potential coefficient C , and is about -10 mV/MPa for the non-fractured country rock zone (this value is in the range of C measured for an intact granite sample in dilute solutions by Ishido and Matsushima¹²⁾). As for the fracture zone, the final asymptotic value is also about -10 mV/MPa. This suggests that the contribution of drag current through the matrix region dominates under steady-state conditions.

(4) Concluding remarks

The present calculations show that the $\Delta SP/\Delta P$

observation is useful for characterizing fractured reservoirs. To detect microscopic $\Delta SP/\Delta P$, an electrode array installed outside the insulated casing is desirable. Such observations were recently reported from an oil field by Chen et al.¹³⁾ To detect macroscopic $\Delta SP/\Delta P$ such as predicted by Ishido and Pritchett⁷⁾, the conductive casing itself (with electrical continuity extending over a distance longer than the typical fracture spacing) can be used as an electrode. In open holes, the appearance of double porosity behavior depends on whether or not a skin zone is present. It may be that skin zones will be found in most open hole completions, so measurements of this type in open holes are likely to be useful.

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