UCRL- 83444
PREPRINT

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U.S. Patent 3,938,711
This paper was prepared for submission to the Geophysical Prospecting

October 5, 1979

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FLUID-FLOW MONITORING USING ELECTROMAGNETIC PROBING*

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ABSTRACT

High-frequency electromagnetic probing is used to monitor the rate and direction of flow of fluids injected into the ground. This method shows the potential for providing more detailed information than procedures presently used. The experimental technique and the test-of-concept experimental results are discussed. This technique has applications in oil-reservoir engineering and in hydrology studies concerning storage of chemical and nuclear wastes.

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INTRODUCTION

When one pumps a fluid into the ground, it is desirable to know where the fluid goes and its rate of advance (Attewell and Farmer 1976). This is important information, for example, in oil-reservoir engineering and in hydrology studies concerning underground storage of chemical and nuclear wastes.

The state of the art for determining where the fluid goes and its rate of flow is presently limited to assumptions of uniform flow rates. This assumption can be erroneous. For example, a common difficulty is that there may be a preferred direction of flow or the flow rate may be spatially dependent (see fig. 1). Electromagnetic waves can be used to monitor the fluid flow and obtain this information, providing the electrical properties of the injected and of the naturally present fluid differ.

METHOD OF MEASUREMENT

Electromagnetic waves can be used to monitor the progress of an injected fluid if such fluid has either a higher or a lower conductivity than the naturally existing fluid. By placing an electromagnetic transmitter in the drill hole into which the fluid is injected and by placing receivers in

auxiliary drill holes around the hole containing the transmitter, one can monitor the signal level in the receivers as the fluid is injected (see fig. 2).

For a constant transmitted power, the receiver signal levels will vary as the injected fluid progresses. Generally speaking, the received signal level should decrease (increase) as the fluid of higher (lower) conductivity progresses. The magnitude of the signal change will depend on the fraction of the region between the transmitter and receiver that is occupied by the injected fluid. In a rough sense, one can intuitively argue that the variation of signal level with time (or progression of injected fluid) should vary approximately as in fig. 3.

MODELING RESULTS

Two simple situations are considered here. In both cases, the transmitter and the receiver are located on opposite sides of the boundary that separates the injected fluid from the fluid naturally present in the medium. For mathematical convenience, the boundary separating these two regions is assumed to be either planar or spherical (see fig. 4). Both the transmitter and receiver are considered to be infinitesimal in length and of unit current moment. The exact formulas for these situations

have been developed for other applications (Wait 1964, Baños 1966, Lager and Lytle 1975). Approximate ray-optic formulas for the situation of a general boundary separating two regions have been developed elsewhere (Lytle, Lager, Laine, and Salisbury 1976).

We have made a number of comparisons between exact and approximate results. The media parameters, separations between transmitter and receiver, and operating frequencies were chosen to be representative of the experimental conditions at in situ coal gasification sites near Kemmerer and Hoe Creek, Wyoming (Davis, Lytle, and Laine 1979). Thus, $\epsilon_{r1} = 10$ (relative dielectric constant), $\epsilon_{r2} = 10$, $\sigma_1 = 0.001$ S/m (resultant conductivity after injection of a low-conductivity fluid) or $\sigma_1 = 0.1$ S/m (resultant conductivity injection of a high-conductivity fluid), $\sigma_2 = 0.01$ S/m (conductivity of the medium that contains naturally occurring fluids), $f = 10$ Mhz, and the separation between transmitter and receiver is 10 m (unless stated otherwise). All conclusions are based on these particular model parameters. It is possible that with other parameters the conclusions might be altered.

Planar boundary situation

Figure 4(a) depicts a transmitter on one side of a planar boundary that separates two media of differing electrical

character. The receiver is on the other side of the planar interface. The effect of the moving fluid-front boundary has been simulated by varying the location of the planar interface. A constant input power to the transmitter is assumed.

We have done this simulation for various transmitter and receiver orientations and have found little effect of transmitter and receiver orientations on the results. Sample results given in fig. 5 (high-conductivity fluid injection) and in fig. 6 (low-conductivity fluid injection) are representative of those for other transmitter and receiver orientations. The exact results are based on the appropriate Sommerfeld integral formulas. The approximate results are based on the generalized ray-optic formulas.

Note in figs. 5 and 6 the almost pure exponential variation of signal strength and the linear phase shift because of the advancing fluid front. There are no noticeable near-field or refraction effects. Results not shown here indicate that when the injected fluid creates a medium conductivity of 10^{-1} S/m (high conductivity), there is little apparent refraction or near-field effect, regardless of the skewness of the orientation relative to the planar boundary. When the injected fluid creates a medium conductivity of 10^{-3} S/m (low conductivity), there is little refraction or near-field effect for small

deviations from normal, but there is some refraction or near-field effect for a skew orientation relative to the planar boundary.

It appears from these planar results that the simple ray-optic representation can be a valid representation of the physical interaction. This is particularly true for a high-conductivity fluid injection (and in some cases even for a low-conductivity fluid injection).

Spherical boundary situation

We also have modeled the situation of a transmitter interior to a sphere and a receiver exterior to the sphere (fig. 4b) to determine the effect of the radius of curvature of the interface (i.e., non planar) on the results. The exact results for this situation are based upon the formulas given previously (Wait 1964) for another problem. An approximate ray-optic formula can also be constructed for this situation to account for the finite radius of curvature of the transmission interface.

We have looked at a number of situations that involve sources located at some distance from the center of the sphere. Representative results, shown in figs. 7 and 8, indicate that the exact and the ray-optic formulas agree relatively well. It appears that radius of curvature or near-field effects become important, for the parameters considered, only for radii less than 1 m.

We believe, on the basis of such canonical modeling for planar and spherical boundaries, that the reduction of the attenuation and phase-shift data (using approximate ray-optic formulas) shows great promise for locating the fluid front between various transmitter and receiver locations.

General boundary situation

The reduction of high-frequency electromagnetic data, using the ray-optic approach, for recognizing a general fluid-front profile appears promising. This appears slightly more promising for a saline fluid than for a low-conductivity fluid injection. Another nice aspect of injecting a saline solution is that there is increased attenuation and thus better resolution of the profile. One difficulty with using saline injection is that higher transmitter powers are needed to ensure successful propagation from transmitter to receiver. In some situations, this increased power level may be so prohibitive that an injection of lower conductivity must be used.

There is also another approach worth mentioning, namely, the idea of generating a multicell model of the fluid front using the technique of geotomographic data collection/interpretation (Dines and Lytle 1979). Recent advances in the art of computerized tomographic imaging of the human head and torso show promise for applications in geophysics. We have adapted

these tomographic techniques for determining the location of the saline front for a particular multicell model. The problem considered concerns a planar section of a 300-ft vertical section of ground that is located between two drill holes separated by 100 ft.

An interrogation of the medium is performed by transmitting between a number of sources in one drill hole and a number of receivers in the other drill hole. By assuming a ray-optic straight-line propagation path, we have numerically simulated the received signal for various situations. An anomalous (more permeable) region ahead of the nominal saline front is assumed in the model so we may determine the degree of resolution of anomalous regions. To monitor the effect of the saline advance, the nominal saline front was modeled at two different distances from the injection hole.

Results of simulation tests for perfect data are depicted in grey level photographs of the conductivity regions between the drill holes (see fig. 9). These results show that the geotomographic method delineates a saline region from the nonsaline region for perfect data. The size of the inferred saline region is slightly larger than the actual saline region size. Note that one can discern not only the nominal saline front but also pick out the anomalous leading edge.

EXPERIMENTAL OBSERVATIONS

We conducted two experiments in the field using high-frequency probing to discern fluid flow. These experiments were performed as part of in situ coal gasification experiments done near Kemmerer and near Hoe Creek, Wyoming.

The first experiment, at Kemmerer, was to test whether the technique was feasible. The experimental configuration was not of our choosing as our experiment was an add-on. Thus, the experiment consisted of a transmitter and a receiver located in drill holes on opposite sides of the fluid-injection hole. This differed from the desired experiment where the transmitter and the fluid injection point would be in the same drill hole. A saline solution was injected, and the received signal level for a constant transmitted power was monitored as a function of time.

The experimental result is shown in fig. 10. As soon as the saline solution was injected, its presence was noted electromagnetically. As time progressed and salt water continued to be injected, the monitored signal decreased even more, as was expected.

In the second test experiment, at Hoe Creek, the transmitter and receiver boreholes were located on opposite sides of the fluid-injection borehole. In this experiment,

low-conductivity water was injected. The resulting qualitative behavior in fig. 11 is exactly what one would expect for low-conductivity injection.

CONCLUSIONS

When a fluid is injected into a medium and the electrical properties of the injected and the naturally present fluid differ, high-frequency electromagnetic monitoring may be used to determine the location and rate of advance of the injected fluid front. By placing a transmitter in the same drill hole in which the fluid is injected and placing receivers in nearby drill holes, we obtain a three-dimensional fluid-flow profile by monitoring the time variation of the attenuation and the phase shift between the transmitter and the receivers. Both the attenuation and phase shift contain significant and interpretable data. A simple data interpretation method is proposed and is given credence by calculations for fluid-flow profiles with known solutions. Injecting a relatively more saline solution, rather than a solution of lower conductivity than is naturally present, appears to yield the more reliable information. Test-of-concept experiments in field situations yielded results consistent with expectations.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore Laboratory under contract No. W-7405-Eng-48. Financial support was provided by the Lawrence Livermore Laboratory In Situ Coal Gasification Program (directed by Doug Stephens) and the Engineering Research Division (directed by Lynn Cleland). The authors thank Ross Castleton and Greg Myers for their computer programming efforts. Helpful discussions concerning this concept were held with our colleagues, Jim Cramer, Neil Davies, Al Duba, and Ed Miller.

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FIGURE CAPTIONS

Fig. 1. Nonuniform flow pattern of fluids injected into the ground shows preferred directions of flow and spatially dependent flow rates.

Fig. 2. Locating the fluid front is feasible by monitoring the transmission loss and phase shift between transmitting and receiving antennas. The injected fluid has an electrical character that differs from that of the fluid naturally present in the medium.

Fig. 3. Change in signal amplitude with start of fluid injection. The character of the transmission between transmitter and receiver indicates the conductivity contrast between the injected and natural fluids and also indicates when the injected-fluid-flow pattern encompasses both the transmitter and receiver. Injection of a high-conductivity fluid gives a greater change in signal than a low-conductivity fluid and hence should give better resolution.

Fig. 4. Canonical problems with exact solutions used to test the validity of approximate ray-optic formulas. (a) Planar boundary. (b) Spherical boundary.

Fig. 5. Planar boundary situation when high-conductivity fluid is injected. As the thickness z_t of the injected fluid is decreased, the levels of the exact and approximate relative signal magnitudes (a) and the phase shifts (b) all increased.

($z_t + z_r = 10$ m, $\epsilon_{r1} = \epsilon_{r2} = 10$, $f = 10$ MHz, $\rho = 5$ m, $\alpha = \beta = 45^\circ$, $\sigma_1 = 0.1$ S/m, and $\sigma_2 = 0.01$ S/m).

Fig. 6. Planar boundary situation when low-conductivity fluid is injected. As the thickness z_t of the injected fluid is decreased, the levels of the exact and approximate relative signal magnitudes (a) and the phase shifts (b) all decreased.

(Conditions are same as in fig. 5 except $\sigma_1 = 0.001$ S/m.)

Fig. 7. Spherical boundary situation where sphere contains a high-conductivity fluid. As the radius of the sphere is increased, the levels of the exact and approximate relative signal magnitudes (a) and the phase shifts (b) all decreased.

($R_r = 10$ m, $R_t = 1$ m, $\epsilon_{r1} = \epsilon_{r2} = 10$, $\sigma_1 = 0.1$ S/m, $\sigma_2 = 0.01$ S/m, $f = 10$ MHz).

Fig. 8. Spherical boundary situation where sphere contains a low-conductivity fluid. As the radius of the sphere is increased, the levels of the exact and approximate relative signal (a) and the phase shifts (b) all increased. Conditions are the same as in fig. 7 except $\sigma_1 = 0.001$ S/m.

Fig. 9. Pictorial representations: (a) An early time ideal image of a region of higher conductivity ($\sigma = 0.002$ S/m) within a lower conductivity host medium ($\sigma = 0.001$ S/m). (b) The geotomographic interpretation of cross-borehole data collected for situation in (a). (c) A later time (i.e., after the injected fluid has moved farther) ideal image of a region of higher conductivity within a lower conductivity host medium. (d) The geotomographic interpretation of cross-borehole data collected for situation in (c). (e) The gray level scale used to represent conductivity.

Fig. 10. The observed signal-level dependence on time when the transmitter and receiver were each located in drill holes on opposite sides of and each 4.6 m from the fluid-injection hole. A constant transmitted power was generated as the saline fluid was injected. The gaps in the curve occurred when the supply of saline solution nee ' replenishing.

Fig. 11. Effect of injection of low-conductivity fluid on observed signal level. The transmitter was 9.4 m to one side of the injection borehole and the receiver was 5.5 m to the other side.

Lytle - Fig. 5

Lytle - Fig. 6

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Lytle - Fig. 11