SAND98-1927C

Flow-Dimension Analysis of Hydraulic Tests to Characterize Water-Conducting Features

Richard L. Beauheim
Sandia National Laboratories, USA

Randall M. Roberts
Duke Engineering & Services, Inc., USA

Abstract

Most analytical solutions and computer codes for well-test analysis assume a radial flow geometry around a well even though actual flow geometries can be quite different, particularly in fractured media. Accurate estimation of hydraulic parameters requires knowledge of the flow geometry. Flow dimensions, representing the combined effects of flow geometry and variations in hydraulic properties, can be interpreted from the late-time slope of the pressure derivative on a log-log plot. However, the interpreted flow dimensions could be caused by an infinite number of flow geometry and hydraulic property combinations. Identifying the correct flow geometry so that appropriate hydraulic properties can be calculated is a difficult process, requiring additional information from a variety of sources. Defining a "conservative" model for a system with nonradial flow dimensions is problematic at best. Errors are compounded when hydraulic properties interpreted by force-fitting radial models to tests in nonradial systems are used in flow and transport models that also fail to take proper account of flow geometry. Whatever the flow dimension of a system might be, proper test interpretation and careful model construction, calibration, and testing are required to provide accurate modelling of flow and transport in that system.

Introduction

Hydraulic-test analysis is the inverse process by which the hydraulic properties of a formation (typically hydraulic conductivity, K, and specific storage, S_s) are estimated from well-test data. Flow-dimension analysis is a relatively new approach to hydraulic-test interpretation that incorporates the geometry of the flow system in estimation of hydraulic properties. Instead of making the standard assumption that flow is radial to or from a borehole, which is often incorrect in fractured and/or heterogeneous media, flow-dimension analysis allows estimation of the actual geometry of the flow system and how that geometry may change in space.

DISCLAIMER

DISCLAIMER

Theory

Barker [1] discussed flow systems with constant K and S_s where the flow dimension of the system was related to the power by which the flow area changed with distance from the source and n described the geometry of the system. Flow area in this formulation is given by:

$$Area(r) = b^{3-n} \frac{2\pi^{\frac{n}{2}}}{\Gamma(\frac{n}{2})} r^{n-1}$$

where: n	=	flow dimension
b	=	extent of the flow zone, L
Γ	=	gamma function
r	=	radial distance from borehole, L

Barker defined flow dimension, n, as the power of variation of cross-sectional flow area with radial distance from the borehole plus one. For example, the relationship between flow area and distance in a standard radial system, where b represents the thickness of the system, is given by:

$$Area(r) = 2\pi rb$$

The flow area is seen to vary linearly with distance (r^1), making the flow dimension, by definition, two.

Historically, well-test analysts have approached test data with an assumption that flow is always radial, although sometimes affected by "boundaries" or heterogeneity. They are predisposed to "find" a horizontal line in the pressure derivative (or, more simplistically, a straight line on a semilog plot) and generally "succeed" in doing so no matter how early "boundary" effects are seen. The result is a model with radial flow at early time that is influenced by boundaries at later time. This model may, in fact, be able to simulate the response to a single test, or type of test, quite well, but fail miserably at simulating the responses to other (types of) tests.

Flow-dimension analysis allows simulated matches to test data that could not be achieved using models restricted to radial (n = 2) flow, particularly when, as occurs in heterogeneous systems, the dimensionality of flow changes as the area of influence of a test increases. It is particularly effective when trying to identify unique, consistent models to explain data from different types of tests (e.g., pulse, constant-pressure, constant-rate). The flow dimension(s) interpreted from hydraulic tests can provide feedback on one's conceptual model of a site, because such things as leakage, heterogeneity, channeling, and boundaries are directly represented in flow-dimension values. For instance, in a confined aquifer, areas of reduced transmissivity act to decrease the flow dimension below two, while areas of increased transmissivity cause the flow dimension to increase.

Flow dimensions can be evaluated from standard log-log diagnostic plots of elapsed time versus pressure change and the derivative of pressure change with respect to log time [2]. A radial (n = 2) flow system will have a derivative that is horizontal (has a constant value) at late time on such a plot, while a positive slope of the late-time derivative indicates a subradial flow dimension and a negative slope indicates a greater-than-radial dimension (Figure 1). If the flow dimension maintains a constant value, the late-time derivative data will plot as a straight line with slope, m, given by:

$$m = 1 - \frac{n}{2}$$

Therefore, the flow dimension can be calculated directly from the slope of the late-time derivative. In heterogeneous systems, several constant-slope sections may be evident in the derivative plot, each representing the flow dimension during the corresponding period of the test.

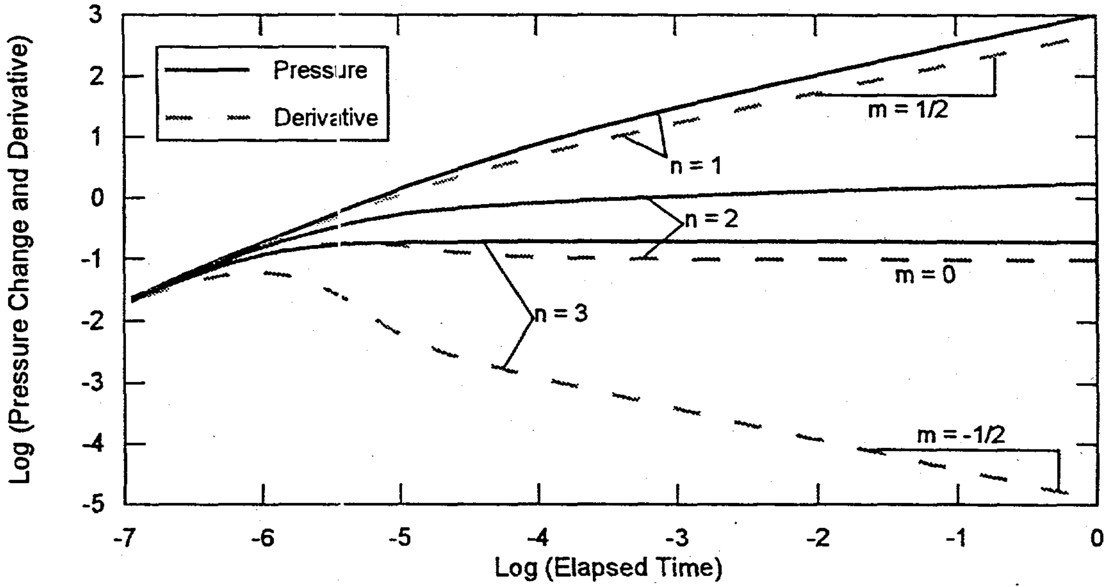

Figure 1. Log-log diagnostic plot showing different late-time derivative slopes (m) for different flow dimensions (n).

However, Doe [3] noted that identical hydraulic responses could be produced in both a homogeneous system with flow area varying as a power of distance and in a constant-flow-area system with hydraulic conductivity and specific storage varying as a power of distance. (As noted by Chakrabarty [4], both K and S_s in the latter case must vary by the same power so that hydraulic diffusivity remains constant.) In fact, hydraulic responses are controlled by the manner in which the product of flow area and hydraulic conductivity changes with distance. In most situations, apparent variations in flow dimensions are likely due to the combined effects of variations in both flow geometry and hydraulic conductivity. Thus, the flow dimension(s) interpreted from a hydraulic test represents a non-unique combination of flow geometry and hydraulic conductivity.

Distinguishing changes in flow geometry from changes in hydraulic conductivity can be of great importance in developing site models of flow and transport. For instance, the surface area for diffusion may be significantly different in a system in which the flow geometry stays the same while hydraulic conductivity changes than in a system in which flow geometry changes while hydraulic conductivity remains constant, even though the hydraulic responses of the two systems are identical. Additional research is needed to determine the effects that uncertainty in the cause of flow-dimension variations has on performance assessment (PA) models and to develop ways of reducing the uncertainty.

Application

A test conducted in the Culebra dolomite at the WIPP site can be used to illustrate the importance of proper flow-system conceptualization. Figure 2 shows the recovery data collected from well H-11b1 after pumping the well for 63 days. Also shown is a conventional interpretation based on an assumption of radial flow at early time. The interpretive model indicates the presence of a negative (enhanced permeability) skin around the wellbore. The pressure derivative appears to be relatively stabilized between 0.03 and 0.3 hr, from which a hydraulic conductivity of 1 x 10^{-5} m/s is interpreted. The rise in the derivative between approximately 1 and 100 hr is attributed to the presence of two non-parallel, no-flow boundaries. The late-time stabilization of the pressure derivative at a value approximately seven times the earlier stabilization value provides the angle at which the no-flow boundaries intersect, 360°/7, or approximately 51°. Thus, the test well is conceptualized as lying in a wedge-shaped aquifer having a hydraulic conductivity of 1 x 10^{-5} m/s.

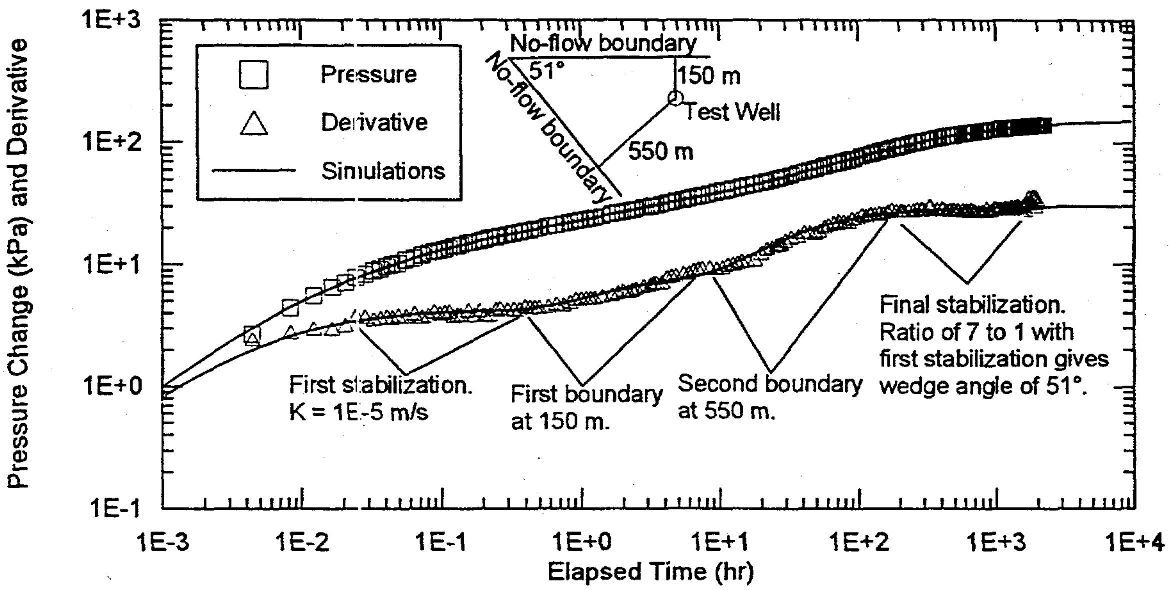

Figure 2. Example of conventional test interpretation assuming radial flow and wedge-shaped boundaries.

Figure 3 shows the same test data matched using a model in which flow dimension is allowed to vary as a function of distance. The data at the beginning of the test are matched using a low, but increasing, flow dimension. The early "stabilization" in the pressure derivative is matched using a subradial flow dimension of 1.65, from which a hydraulic conductivity of 1 x 10^{-4} m/s is interpreted. (Note that the hydraulic conductivity interpreted from the early stabilization is an order of magnitude higher when the flow dimension is assumed to be 1.65 than when it is assumed to be 2.) The subsequent rise in the derivative is represented by a decreasing flow dimension and the late-time stabilization in the derivative is represented by an increasing flow dimension that stabilizes at approximately 2.05. Figure 4 shows how these interpreted flow dimensions change as a function of distance from the well, assuming a constant K.

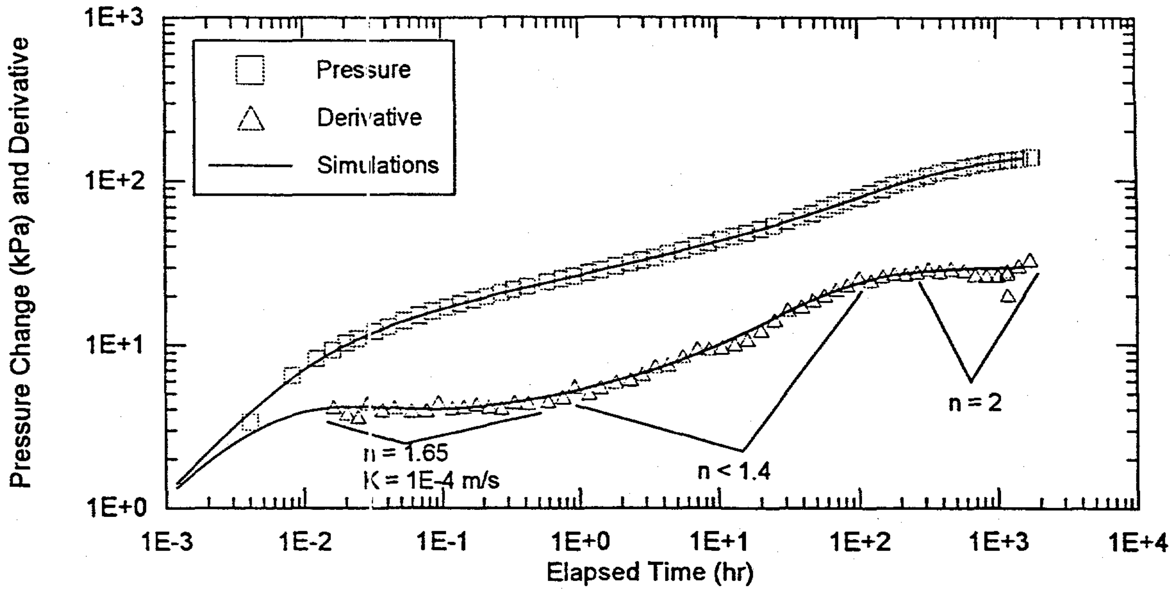

Figure 3. Example of flow-dimension approach to test interpretation with $n = f(r)$.

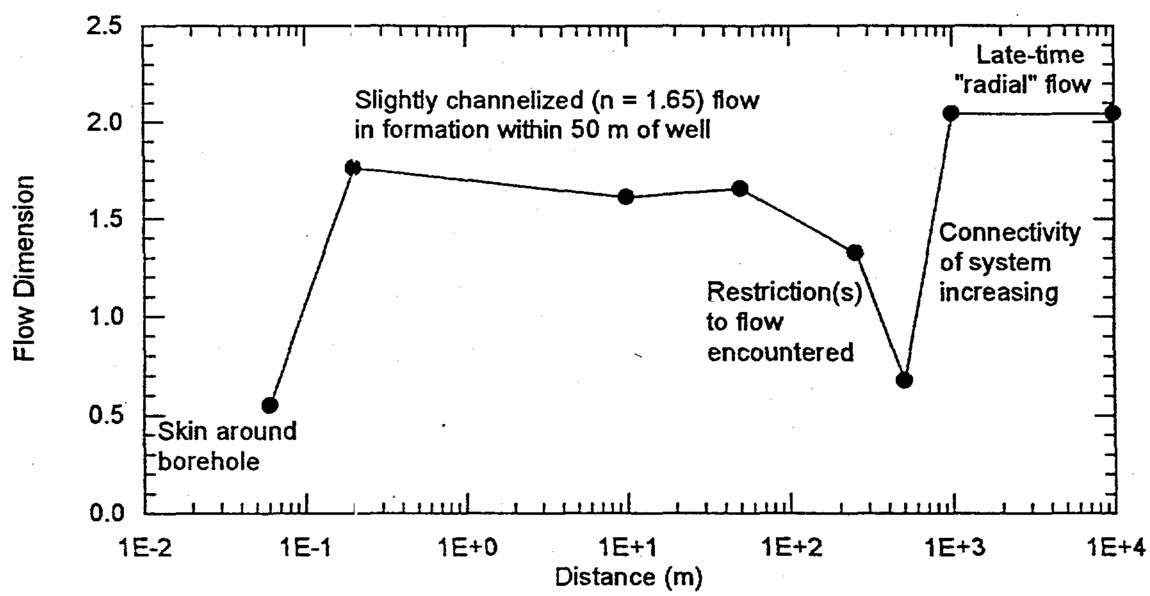

Figure 4. Interpreted flow dimensions assuming constant *K*.

From the flow-dimension analysis, we derive the following conceptualizations of the flow system/aquifer. Assuming that *K* is constant and that all the variability in flow dimension is due to variability in flow geometry, flow is restricted within a skin zone around the well to a fraction of the available area, as might be the case if a fracture intersected the wellbore. The flow dimension then increases and stabilizes at approximately 1.65, indicating channelized flow over a distance of tens of meters. Restrictions to flow are then encountered, perhaps due to fractures pinching out in certain directions. At some distance, the restrictions end and flow is able to spread out approximately radially. Figure 5 shows how the ratio of the area available to flow in this model relative to the area available in a fully radial system changes with distance. By the time the late-time "radial" flow occurs, the area has been reduced to approximately 0.01 of what it would be in a fully radial system.

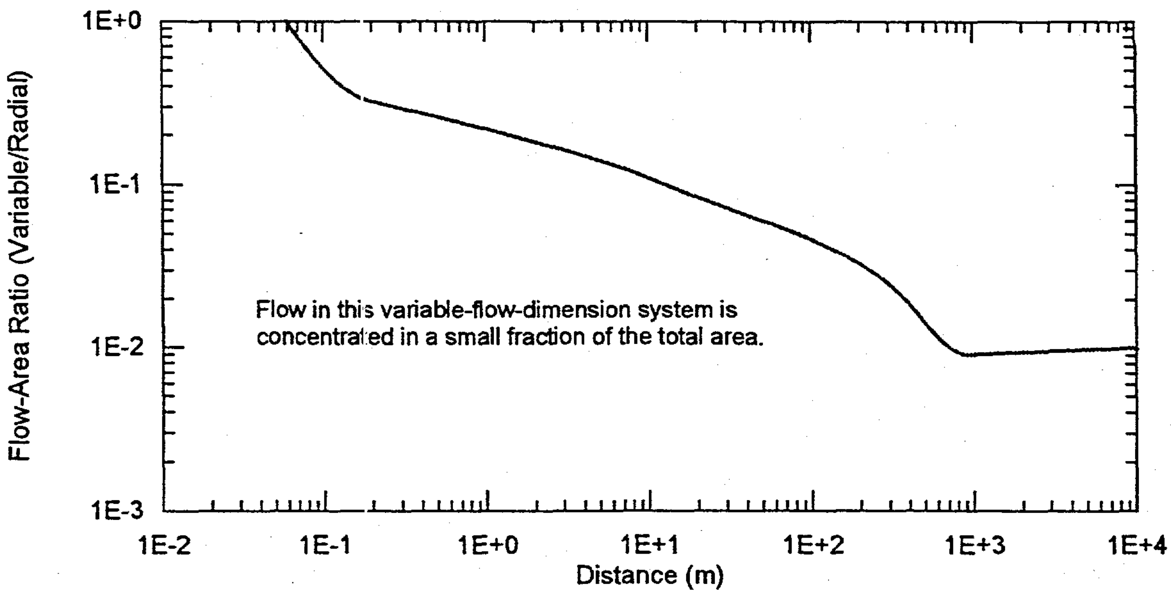

Figure 5. Ratio of flow areas between variable-flow-dimension and radial systems as a function of distance.

Alternatively, we can assume that the flow dimension has a constant value of 1.65 and that all the observed variability is caused by variations in *K*. In this case, *K* at the borehole wall is high but then decreases to the local formation value. After a period of stabilization, *K* decreases before beginning a final, continuing increase. This pattern of change is shown in Figure 6. Variation in *K* while flow dimension remains constant might be caused by locally variable precipitation of minerals in a fracture network having a consistent geometry, causing flow apertures to vary.

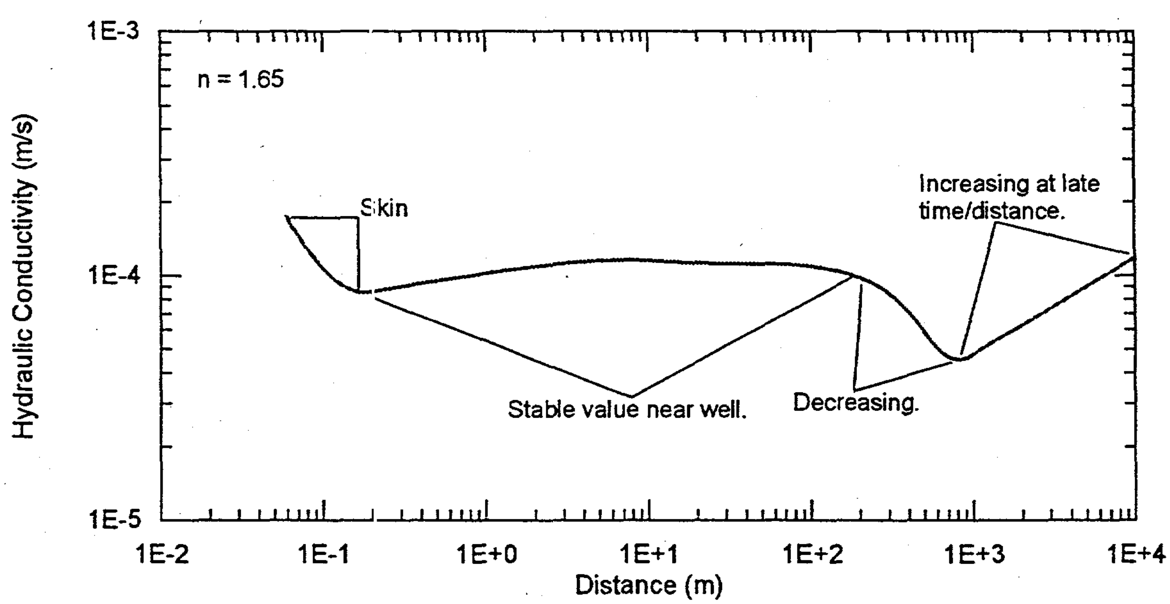

Figure 6. Variation of *K* in a constant-flow-dimension system.

Clearly, the flow-dimension analysis presents information in a more general form than the conventional analysis. The boundaries indicated by the conventional analysis are seen as one of multiple possibilities in the flow-dimension analysis. Constraining the possible number of solutions is a non-trivial task. The flow geometry of a system must be determined before accurate estimates of the hydraulic parameters can be made. Given the high degree of correlation between hydraulic-parameter estimates and flow geometry, along with the potential variability of these parameters in a fractured flow system, several things become apparent: 1) time should be taken to learn how various combinations of hydraulic parameters, geometry, and boundary conditions are reflected in different types of hydraulic tests in the hope of developing diagnostic tools; 2) an adequate analysis methodology should be able to accommodate analyses of all types of hydraulic tests in all types of geometries; and 3) large errors in the hydraulic-parameter estimates can result if the flow geometry is unjustifiably assumed to be radial for analysis purposes.

Incorporating flow-dimension information into site models

At this early stage in our understanding of the implications of nonradial flow dimensions, useful information could be obtained by creating models of domains with different flow dimensions and determining how flow and transport are affected by changing dimensions. Intuitively, for a given flux or given hydraulic conductivity, we would expect Darcy velocities to increase as the flow dimension decreases. Defining a "conservative" model for a system with nonradial flow dimensions might prove to be extremely difficult.

For a particular site, the problem remains to incorporate flow-dimension information obtained from hydraulic tests into flow and transport models of the site. To accomplish this, we recommend that the following five steps be taken: 1) Evaluate the possible factors causing the observed flow dimension(s). This evaluation might include: (a) identification of boundaries (e.g., faults) from geologic data; (b) identification of fracture sets, fracture connectivity, preferred orientations, and aperture variations; (c) deriving information on connectivity and preferential flow paths from the spatial patterns of responses observed during multiwell hydraulic tests; and (d) obtaining information on the characteristics of specific flow paths from tracer tests. 2) Construct a first-generation model of the site incorporating the features and processes thought to be important. Use of a discrete-fracture model or simulated annealing might be required to obtain the desired flow dimensions. 3) Use the model to simulate well tests to determine if appropriate flow dimensions and response patterns have been created. 4) Calibrate the model to observed flow dimensions and responses, obtaining new data as needed. 5) Verify the model by predicting the responses to be observed from a new test.

Summary and conclusions

Although most analytical solutions and computer codes for well-test analysis assume a radial flow geometry around a well, actual flow geometries can be quite different, particularly in fractured media. Accurate estimation of hydraulic parameters requires knowledge of the flow geometry. Flow dimensions, representing the combined effects of flow geometry and variations in hydraulic properties, can be interpreted from the late-time slope of the pressure derivative on a log-log plot. Identifying the flow geometry so that appropriate hydraulic properties can be calculated is a difficult process, requiring additional information from a variety of sources. Defining a "conservative" model for a system with nonradial flow dimensions is problematic at best. Errors are compounded when hydraulic properties interpreted by force-fitting radial models to tests in nonradial systems are used in flow and transport models that also fail to take proper account of flow geometry. Whatever the flow dimension of a system might be, proper test interpretation and careful model construction, calibration, and testing are required to provide accurate modelling of flow and transport.

References

[1] Barker, J.A., "A Generalized Radial Flow Model for Hydraulic Tests in Fractured Rock", *Water Resources Research*, 1988, Vol. 24, no. 10, pp. 1796-1804.

[2] Bourdet, D., J.A. Ayoub, and Y.M Pirard, "Use of Pressure Derivative in Well-Test Interpretation", *SPE Formation Evaluation*, 1989, Vol. 4, no. 2, pp. 293-302.

[3] Doe, T.W., "Fractional Dimension Analysis of Constant-Pressure Well Tests", in *Proceedings 1991 SPE Annual Technical Conference & Exhibition, Formation Evaluation & Reservoir Geology*, SPE 22702, 1991, pp. 461-467.

[4] Chakrabarty, C., "A Note on Fractional Dimension Analysis of Constant Rate Interference Tests", *Water Resources Research*, 1994, Vol. 30, no. 7, pp. 2339-2341.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL8500.