PROCEEDINGS, Twenty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

RESERVOIR CHARACTERIZATION BY INTEGRATED PRESSURE-TRANSIENT AND TRACER-CONCENTRATION/TIME DATA ANALYSIS

Serhat Akin

Middle East Technical University
Petroleum and Natural Gas Engineering Department
Inonu Bulvari 06531 Ankara-Turkey
e-mail: serhat@metu.edu.tr

ABSTRACT

One frequent observation from conventional pressure transient test analysis is that field data match mathematical models derived for homogeneous systems. This observation suggests that pressure data as presently interpreted may not contain details concerning certain reservoir heterogeneities. On the other hand, tracer tests may be more sensitive to heterogeneous elements present in the reservoir because of the convective nature of the flow test. In this study we investigate a possible improvement of conventional pressure transient and tracer test analysis by integrating these two types well-testing methods using the nonlinear least square regression method. To achieve this goal, a correlation between permeability and dispersivity is used to couple the response of both tests. A multi fracture tracer test model was coupled with conventional, fractal, and double porosity pressure models using a commercial spreadsheet. The proposed method is tested using experimental well test and tracer test data obtained from a fractured reservoir model where fracture apertures and distributions were known. It has been observed that the match of multi-fracture tracer test model coupled with dual-porosity-slabs pressure transient model was better than the other combinations. Moreover, this combination described the physics of the experiments better than the others did. It has been also observed that both models showed a nearly unique match.

INTRODUCTION

In petroleum engineering, geothermal engineering, and groundwater hydrology, well tests are conducted routinely to diagnose the well's condition and to estimate formation properties. Well test data may be analyzed to yield quantitative information regarding:

(1) Formation permeability, storativity, and porosity.
(2) The presence of barriers and leaky boundaries,
(3) The condition of the well (i.e., damaged or stimulated)
(4) The presence of major fractures close to the well
(5) The mean formation pressure.

One frequent observation from conventional pressure transient test analysis is that field data match mathematical models derived for homogeneous systems. Sabet (1991) showed that a reservoir that consists of interbedded layers of limestone and dolomite could behave on well tests exactly as if it were a naturally fractured reservoir provided that: the dolomite layers are thin in comparison to limestone; and the rate of flow from limestone into the wellbore is either zero or negligible when compared to the rate of crossflow from the limestone to the dolomite. Mishra and Ramey (1990) showed that conventional pressure testing of constant-outer-boundary-pressure, layered systems without interlayer crossflow produce an integrated response during the infinite acting period from which only total system properties can be calculated. In order to alleviate this problem they suggested the use of tracer test analysis together with core and log analysis, and geophysical/geological analysis. Thus they proposed a synergetic approach.

On the other hand, Acuna et al. (1994) suggested use of fractal well test analysis proposed by Chang and Yortsos (1990) to solve the aforementioned problem. Their approach is based on the assumption that the network of fractures feeding a particular well has fractal properties and may lead to a variety of possible transient behaviors. This assumption can be satisfied if and only if either the reservoir consists of fractures with the same conductance and has the topology of a fractal object, or the fracture network is Euclidian, but the distribution of the fracture conductance is very wide.

Several studies related these problems to the non-uniqueness of the solutions. Carvalho et al (1992) addressed practical methods of applying the nonlinear regression to the analysis of pressure transient data. They presented the use of a two-step procedure, which utilized the pressure-pressure derivative ratio in the first step, was demonstrated to increase the chances of obtaining a unique fit. They also, presented a method of applying "robust" parameter estimation (which accounts for data outliers) that uses commonly available algorithms based on least squares (LS) regression. They demonstrated the applicability of the proposed methods by analyzing several sets of field data.

More recently, Kelly (1996) presented a series of case studies and discussed with a view to establishing that non-uniqueness is sometimes a reality. Furthermore, he demonstrated (through examples) that starting with one mathematical match to pressure data and deriving a geological model is the reverse approach and may be fraught with danger.

In this study, in order to tackle uniqueness problem, we propose a new analysis strategy. We investigate a possible improvement of conventional pressure transient and tracer test analysis by integrating these two types well-testing methods using the nonlinear least square regression method. To achieve this goal, a correlation between permeability and dispersivity is used to couple the response of both tests. Different tracer test models namely homogeneous, double porosity, and fracture models were coupled with a homogeneous or a double porosity transient pressure model using a commercial spreadsheet.

The proposed method is tested using experimental well test and tracer test data obtained from a fractured reservoir model where fracture apertures and distributions were known. It has been observed that the match of multi-fracture tracer test model coupled with dual-porosity-cubes pressure transient model was better than the other combinations. Moreover, this combination described the physics of the experiments better than the others did. It has been also observed that both models showed a nearly unique match.

THEORY

Geothermal wells generally produce from fractured volcanic rocks. As reported by Barenblatt et al (1960), a porous rock with a highly developed system of fissures can be represented as the superposition of two porous media with pores of different sizes. Warren and Root (1963) presented a model based on above mathematical concept of superposition. They idealized a naturally fractured reservoir such that the material with the primary porosity is contained within a systematic array of identical rectangular parallelepipeds. The secondary porosity is contained within an orthogonal system of continuos uniform fractures which are oriented parallel to one of the principal axes of permeability. In this model, the dual porosity effects are described in terms of two parameters that relate primary and secondary properties. The first of the two parameters is the storativity ratio, ω, that relates the fracture storativity to that of the combined flow:

$$\omega = \frac{\phi_f C_{tf}}{\phi_f C_{tf} + \phi_m C_{tm}} \tag{1}$$

Values of ω can be less than or equal to one. The case of ω = 1 occurs if the matrix porosity is zero, hence it implies that the reservoir is a single porosity one (Horne 1995).

The second parameter is dependent on the transmissivity ratio, and is designated as λ:

$$\lambda = \alpha \frac{k_m}{k_f} r_w^2 \tag{2}$$

Here α is a factor that depends on the geometry of the interporosity flow between the matrix and the fractures:

$$\alpha = \frac{A}{xV} \tag{3}$$

where A is the surface area of the matrix block, V is the matrix volume, and x is a characteristic length. If the matrix blocks are cubes or spheres, then the interporosity flow is three dimensional and λ is given by

$$\lambda = \frac{60 k_m}{x_m^2 k_f} r_w^2 \tag{4}$$

Here x_m is the length of a side of the cubic block, or the diameter of the spherical block. If the matrix blocks are long cylinders, then the interporosity flow is two dimensional and λ is given by

$$\lambda = \frac{32 k_m}{x_m^2 k_f} r_w^2 \tag{5}$$

where x_m is now the diameter of the cylindrical block. If the matrix blocks are slabs overlying each other with fractures in between, then the interporosity flow is one dimensional, and λ is given by

$$\lambda = \frac{12 k_m}{h_f^2 k_f} r_w^2 \tag{6}$$

Here h_f is the height of the secondary porosity slab.

Values of λ are usually very small (usually, 10^{-3} to 10^{-10}). If the value of λ is larger than 10^{-3}, the level of heterogeneity is insufficient for dual porosity effects to be of importance, and again the reservoir acts as a single porosity (Horne 1995) as in the case of ω= 1.

Analysis of pressure transient tests is usually conducted by combining type-curve matching and semi-logarithmic techniques in a computer-aided manner (Horne, 1995).

Tracer Models

The flow of tracer between an injection and a production well pair has been described both analytically and numerically by a number of authors. In this study, a multi-fracture model (Fossum and Horne 1982) was considered. Several other models like fracture-matrix model (Bullivant and O'Sullivan, 1989), uniform porous model (Sauty 1980), double porosity slabs model, double porosity cubes model, and double porosity pseudo steady state model (Bullivant and O'Sullivan, 1989) could also be used. In multi fracture model it is assumed that there is a good connection between the injection and production wells along a streamline, which is surrounded by a stream tube of constant cross section. The tracer is injected as a slug from the injection well and the response is recorded in the observation well. The details of the models can be found elsewhere (Akin and Okandan, 1995).

METHOD OF SOLUTION

Since, heterogeneity is one of the causes of the dispersion effect, the coeeficients of dispersion should be a function of permeability. Harleman et al (1963) presented empirical expressions relating permeability to dispersivity. Bear (1972) provided an expression relating the permeability of the medium to the longitidunal dispersivity, to porosity, to some characteristic pore cross-section and to some chracteristic pore length. More recently, Deng and Horne (1995) reformulated the convection-dispersion equation and diffusion equation to a system of first order equations in permeability. Then they solved the resulting system of equations to obtain the permeability distribution. Thus we follow Deng and Horne (1995) and use the following definition of dispersion coefficient that can be related to the permeability of the medium as follows:

$$D_{ij}(x,u) = \phi d_m I + \frac{1}{|u|}\begin{pmatrix} (d_l + d_t)u_x^2 & (d_l - d_t)u_x u_y \\ (d_l - d_t)u_x u_y & (d_l + d_t)u_y^2 \end{pmatrix} \tag{7}$$

$$u = (u_x, u_y) = -\frac{k}{\mu}\nabla p \tag{8}$$

$$|u| = \sqrt{u_x^2 + u_y^2} = \frac{k}{\mu}\sqrt{\left(\frac{\partial p}{\partial x}\right)^2 + \left(\frac{\partial p}{\partial y}\right)^2} \tag{9}$$

Substitute 25 and 26 into 24, we will have

$$D_{ij}(x,u) = \phi d_m I + \frac{d_l k}{|\nabla p|\mu}\begin{pmatrix} \left(\frac{\partial p}{\partial x}\right)^2 & \left(\frac{\partial p}{\partial x}\right)\left(\frac{\partial p}{\partial y}\right) \\ \left(\frac{\partial p}{\partial x}\right)\left(\frac{\partial p}{\partial y}\right) & \left(\frac{\partial p}{\partial y}\right)^2 \end{pmatrix} + \frac{d_t k}{|\nabla p|\mu}\begin{pmatrix} \left(\frac{\partial p}{\partial x}\right)^2 & -\left(\frac{\partial p}{\partial x}\right)\left(\frac{\partial p}{\partial y}\right) \\ -\left(\frac{\partial p}{\partial x}\right)\left(\frac{\partial p}{\partial y}\right) & \left(\frac{\partial p}{\partial y}\right)^2 \end{pmatrix} \tag{10}$$

This equation relates permeability to dispersion coefficient. The developed analytical pressure transient and tracer models were implemented on commercially available spreadsheet software (Microsoft Excel) for convenience as reported by Akin and Okandan (1995). Model pressure transient and tracer data was then matched to experimental data using least squares approximation with a combination of a well-known nonlinear optimization code namely GRG2 (Lasdon and Waren, 1989) which is also utilized in the spreadsheet software (Microsoft Excel User's Guide, 1992). By minimizing the following objective function R, the parameters C_m and P_m can be estimated.

$$R = \sum_{i=1}^{n} W_c (C_m - C_{obs})^2 + W_p (P_m - P_{obs})^2 \tag{11}$$

In nonlinear parameter estimation or curve fitting, it is important to have good initial estimates for the model parameters. Tracer model parameters like the peak time and response start time can be easily found from the test data. However, initial estimates for the nonlinear parameters (i.e. Peclet number) should be carried out in trial and error fashion. Likewise, pressure transient model parameters are estimated in a similar manner. The methodology can be summarized as follows. First the problem is defined by specifying the target cell (R), changing cells (P_e, etc.), and the constraints (P_e>0, etc.). Following that, defining the solution time, number of iterations, and the precision of constraints controls the solution process. Then the method used by the "Solver" is defined. At this point, the estimation technique (tangent or quadratic), the method for calculating derivatives (central difference equation or forward difference equation), and finally the search method (quasi-Newton or conjugate) must be defined.

After the “Solver” has found a solution, to specify the goodness of the estimate, confidence intervals of the changing parameters were found. Using 95 % confidence intervals to evaluate the goodness of fit of a nonlinear regression analysis of tests, it was observed that an acceptable estimate was the one with a confidence interval that is 10% of the value itself. If the confidence interval of one of the changing parameters exceeds the aforementioned value, initial estimates of the changing parameters were readjusted and/or the search direction and the estimates were changed until a reasonable value was achieved. It should be noted that, the confidence interval is a function of noise in the data, as well as the number of data points, and the degree of correlation between the unknowns.

RESULTS AND DISCUSSIONS

The models were tested using an experimental set of data. In the experimental work, tracer flow in a fractured geothermal model with zero matrix permeability was considered (Bayar 1987, Akin and Okandan, 1995). A three-dimensional fractured model, which was composed of 70 non-porous and non-permeable marble blocks having three different dimensions was used (Figure 1). Marble blocks were stacked on top of each other freely (i.e. without a spacer). An insulated steel box frame of 60x60x60 was used to cover the fractured medium created and porosity of the medium was determined as 4% (5850 cc pore volume). Potassium Iodide (KI) solution was used as the chemical tracer and it was injected from the top diagonal corner of the model and production concentration of the tracer was monitored from the bottom end of the diagonal. Injection and production port locations were changed as top-top, bottom-top, top-bottom, and bottom-bottom to observe the effect of longer flow path. Volume of KI slug injected was same, one third of the pore volume with the concentration of 4000 ppm in all experiments. During the reinjection experiments temperature profiles as well as pressure data were recorded at regular time intervals (Arpaci, 1988). The tracer experiments’ results are presented as breakthrough curves where effluent concentration is plotted versus time.

Depending on the injection-production scheme, different pressure responses were observed as it can be seen from Fig 2. Following that several pressure transient models were used to fit the experimental data. The analytical models used were as follows: conventional, double porosity pseudo steady state, double porosity slabs, double porosity spheres, and fractal model. As it can be observed from Fig 3 through 6 both models described the experimental data pretty good.

Infinite acting homogeneous model considering storage and skin is one of the most generally used well test models to represent geothermal reservoir conditions. Large wellbore storage coefficient is common in geothermal wells due to the large wellbore volume and the compressibility of the steam-water mixture in the wellbore. Table 1 presents the results of the analyses obtained using this model. Large, negative skin values calculated are consistent with the theory that since geothermal wells generally produce from fractured volcanic rocks they show stimulated behavior (Horne 1995). However, fracture width values calculated from the permeability data (Reiss 1980) overestimated the mechanical fracture aperture many times.

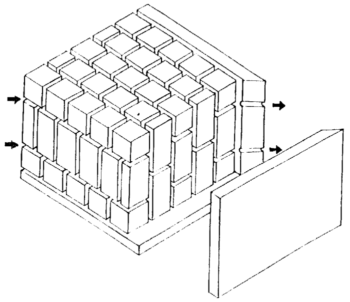

Figure 1. Schematic-Drawing of the Laboratory Geothermal Reinjection Model (After Bayar, 1987).

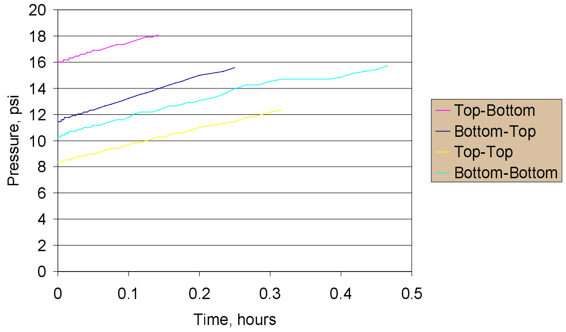

Figure 2. Pressure response of different injection production locations.

Table 1. Results obtained using the infinite acting homogeneous storage and skin model.

	Top-Bottom	Bottom-Top	Top-Top	Bottom-Bottom
k, md	21.36	117.31	61.29	75.34
b, μm	98.09	229.87	166.16	184.22
skin	-8.17	-1.88	-3.27	-3.47
Cde2S	8.67E+00	2.72E+05	1.72E+04	9.95E+03

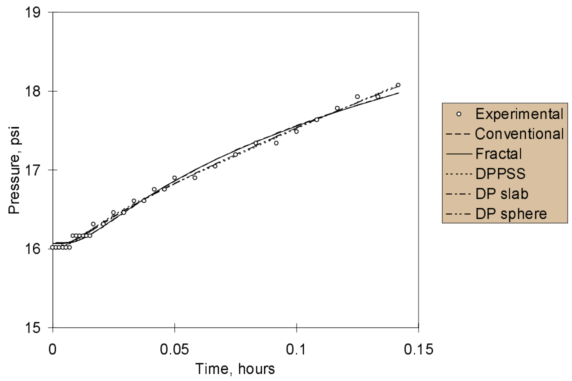

Figure 3. Pressure interference test top injection-bottom production.

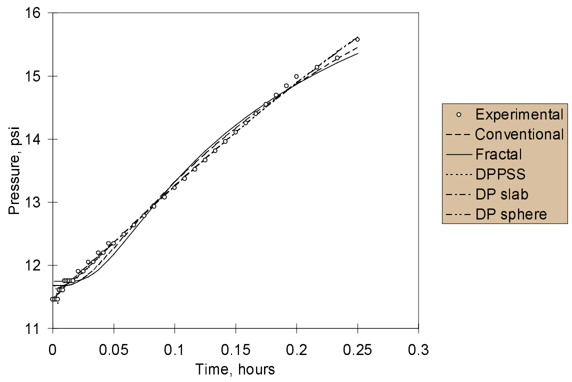

Figure 4. Pressure interference test bottom injection-top production.

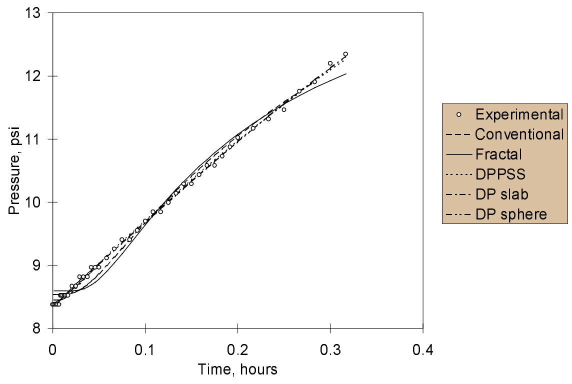

Figure 5. Pressure interference test top injection-top production.

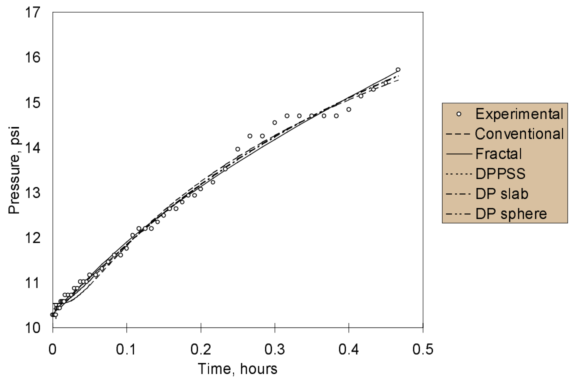

Figure 6. Pressure interference test bottom injection-bottom production.

The second model used to match the experimental data is recently introduced fractal model. There are two important parameters in a fractal pressure transient model: the fractal dimension, d_{mf}, and the connectivity of the fractal fracture network, θ. The fractal dimension represents a key geometric property of the fracture network and varies between 1 and 3. The fracture density is a function of the fractal dimension. The connectivity parameter characterizes diffusion or conduction in the fracture network. When the connectivity is zero, the diffusion process is a classical random walk. In a fractal network this parameter is usually greater than one. Unfortunately there is no established relation between d_{mf} and θ (Acuna et al 1992). Table 2 summarizes the results obtained for the fractal model.

Table 2. Results obtained using the fractal model.

	Top-Bottom	Bottom-Top	Top-Top	Bottom-Bottom
k=	29.51085	51.72279	113.4418	17.34882
ϕc_t=	6.89E-05	3.36E-04	9.96E-04	2.85E-05
θ=	0.282587	1.96E-05	1.38E-04	0.310444
d_{mf}=	1.579171	1.905324	1.956296	1.296168
P_i=	14.90539	6.466279	3.058177	9.806754

The final set of models considered was storage-skin double porosity pseudo steady state, slabs, and spheres models. Sums of square residuals obtained from these models were better than the second model. Moreover, the fracture apertures were much better than the previous models and the lambda values were consistent with zero matrix permeability of the physical model. However, some of the omega values were many times larger, suggesting an almost homogeneous system. An interesting observation was that the storage values were somewhat small which is not common in geothermal well tests.

However, all of the models responded in different matches. Table 1 presents the permeability obtained after these matches. The magnitude of the permeability is nearly the same for all but the fractal model.

Table 3. Results obtained using the double porosity models

Double Porosity Pseudo Steady State Model

	Top-Bottom	Bottom-Top	Top-Top	Bottom-Bottom
K=	6.251011	4.953641	5.5149	7.314191
ϕc_t=	3.42E-05	2.85E-05	3.66E-05	3.22E-05
C_D	65.22559	42.48419	499	393.7765
Skin	-5.77738	-10.8015	-2.7829	-4.00218
ω=	0.244496	0.438474	0.30346	0.214745
λ=	5.32E-05	4.66E-05	5.21E-05	7.44E-05

Double Porosity Slabs Model

K=	7.522655	5.468459	4.899447	7.230329
ϕc_t=	3.49E-05	2.68E-05	3.64E-05	3.18E-05
C_D	85.47381	3.825289	36.93811	4.942771
Skin	-5.60408	-14.8534	-4.90494	14.38219
ω=	0.20711	7.32E-06	4.07E-06	2.84E-05
λ=	5.42E-05	1.17E-04	1.10E-04	1.00E-04

Double Porosity Spheres Model

K=	8.01838	1.88776	4.119212	7.432999
ϕc_t=	3.38E-05	3.68E-05	3.86E-05	3.35E-05
C_D	21.23579	56.25648	2.877512	186.9972
Skin	-7.57645	-4.19382	-14.8596	-5.60845
ω=	3.63E-04	2.31E-02	1.08E-05	0.434291
λ=	7.21E-05	6.36E-05	1.00E-04	6.35E-05

Following the method of solution outlined in the previous sections, we have tried to improve the matches and thus the analyses. Figure 7 shows the effluent concentration profile for tracer tests conducted using the same model with different producer-injector configurations. Multi-peaked profiles reflect the effect of longer and different paths of travel. Double porosity models as opposed to fractal and conventional skin and storage models were selected, as these models were most reflective of the physics of the experiments.

In all matches equation 11 with inverses of variances of the experimental data being the weighting factors was utilized. Figures 8 through 15 show the pressure and transient matches for all injection-production schemes. Numerically, we have observed an improvement in all matches. Moreover, we have also observed that most of matches were the same even if different models were utilized. Table 4 summarizes the results obtained after these matches. It can be observed that relatively high storativity and interporosity values were obtained when compared to previous matches. High wellbore storage values are common in geothermal wells due to the large wellbore volume and the compressibility of the steam-water mixture in the wellbore. It was also observed that skin factors are positive.

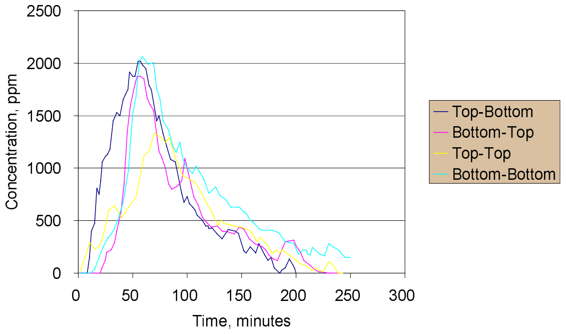

Figure 7. Effluent concentration-time plots for different injection-production schemes.

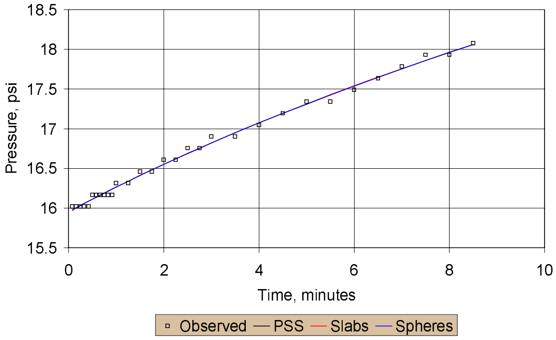

Figure 8. Pressure interference test top injection-bottom production.

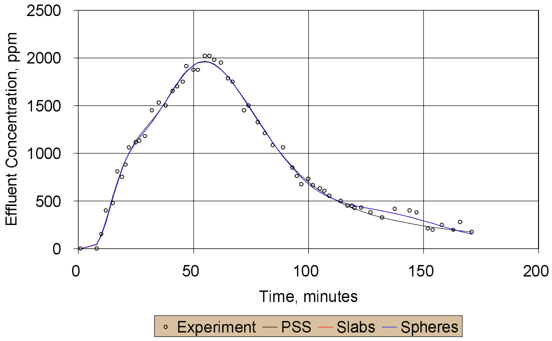

Figure 9. Tracer test top injection-bottom production.

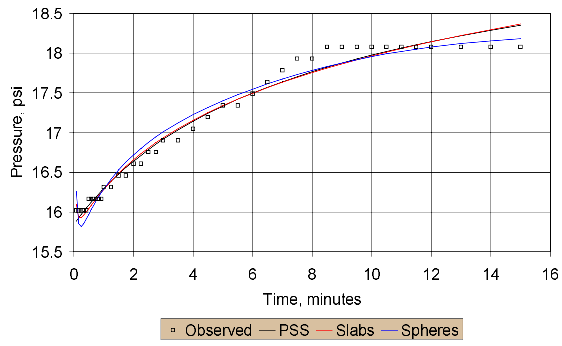

Figure 10. Pressure interference test bottom injection-top production.

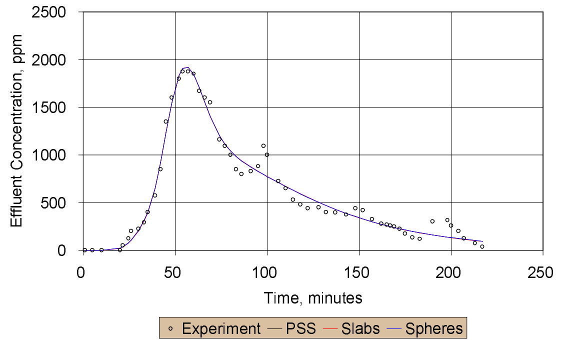

Figure 11. Tracer test bottom injection-top production.

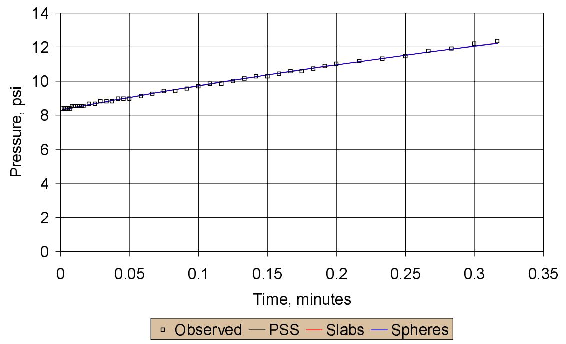

Figure 12. Pressure interference test top injection-top production.

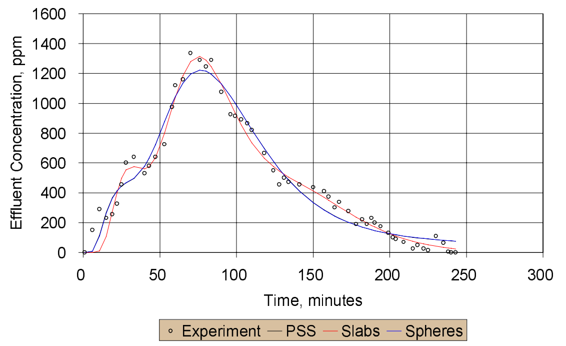

Figure 13. Tracer test top injection-top production.

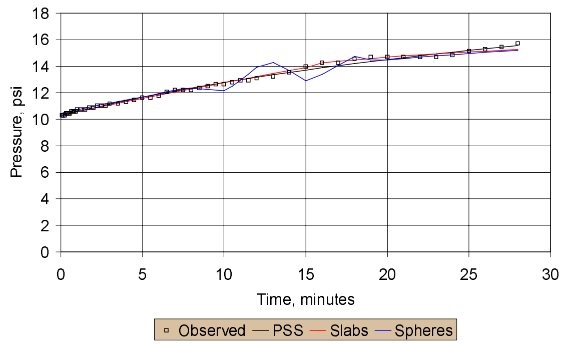

Figure 14. Pressure interference test bottom injection-bottom production.

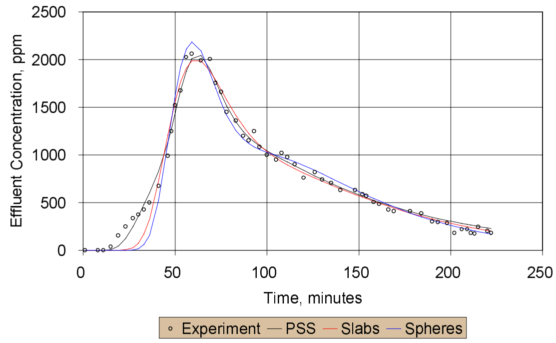

Figure 15. Tracer test bottom injection-bottom production.

Table 4. Results obtained with combined match technique using the double porosity models

Double Porosity Pseudo Steady State Model

	Top-Bottom	Bottom-Top	Top-Top	Bottom-Bottom
K=	3890.938	2225.531	15004.91	1872.051
ϕc_t=	0.000987	5.84E-05	0.000784	0.172418
C_D	167643.7	57555.98	125035.5	1136.055
Skin	0.046886	0	0.050194	0.655019
ω=	0.014078	0.014078	0.014078	0.014029
λ=	1.186529	1.18654	1.186529	1.06981

Double Porosity Slabs Model

K=	552.2103	1029.74	758.7764	1816.662
ϕc_t=	0.001082	0.012443	2.725156	0.113752
C_D	202299.5	262.5208	0.000377	1699.213
Skin	0.404226	0	3.231314	0.548006
ω=	0.010584	0.011469	0	0.01393
λ=	0.521702	0.141644	1.010157	0.110662

Double Porosity Spheres Model

K=	417.054	2066.952	585.3548	1816.611
ϕc_t=	2.15E-03	0.000177	2.794368	0.164991
C_D	108465.8	18801.7	0.000835	1216.994
Skin	0.22589	0.0001	1.701258	0.727037
ω=	1.05E-02	0.0001	0	0.013958
λ=	6.60E-01	0.0001	0.474231	0.004087

These results suggest that the system under investigation act like a homogeneous system. Thus it can be concluded that even though the matches improved, the effect of heterogeneity disappeared. Thus, a further improvement using derivative values is necessary.

CONCLUSIONS

Spreadsheet models that incorporate pressure transient and multi fracture tracer models are developed. Using the developed models, improvement of conventional pressure transient and tracer test analysis by integrating these two types well-testing methods is discussed. Nonlinear least square regression method is used together with a correlation between permeability and dispersivity to couple the response of both tests. The proposed method is tested using experimental well test and tracer test data obtained from a fractured reservoir model where fracture apertures and distributions were known. It has been observed that the match of multi-fracture tracer test model coupled with dual-porosity-slabs pressure transient model was better than the other combinations. Moreover, this combination described the physics of the experiments better than the others did. It has been also observed that both models showed a nearly unique match.

REFERENCES

Acuna, J. A., Ershaghi, I. And Yortsos, Y. C., 1992. “Practical Application of Fractal Pressure-Transient Analysis in Naturally Fractured Reservoirs”, paper SPE 24705 presented at the SPE Annual Technical Conference and Exhibition held in Washington D.C. Oct. 4-7.

Akin, S. and Okandan, E., 1995. “Reservoir Characterization by Tracer Testing”, presented at the World Geothermal Congress 1995, 18-31 May, Florence, Italy.

Arpaci, M., 1988. “Transient Behavior and Tracer Flow in a Fractured Geothermal Model with Zero Matrix Permeability”, Msc. Thesis, METU, Ankara, Turkey.

Baldwin, D. E. Jr., 1966. “Prediction of Tracer Performance in a Five-Spot Pattern”, JPT, April 513-17.

Barrenblatt, G. I., Zheltov, I. P and Kochina, I. N., 1960. ”Basic Concepts in the Theory of Homogeneous Liquids in Fissured Rocks”, J. Appl. Math. Mech., No 24, 1286-1303.

Bayar, M. 1987. “Tracer Testing in a Fractured Geothermal Reservoir Model”, Msc Thesis, METU, Ankara, Turkey.

Carvalho R.S., Redner, R.A., Thompson L.G., Reynolds A.C.: “Robust Procedures for Parameter Estimation by Automated Type-Curve Matching,” paper SPE 24732 presented at the 67th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers held in Washington, DC, October 4-7, 1992.

Da Prat, G., 1990. ”Well Test Analysis for Fractured Reservoir Evaluation”, Elsevier, Science Publishing Company Inc., New York, USA.

Fossum, M.P. and Horne, R. N., 1982. “Interpretation of Tracer Return Profiles at Wairakei Geothermal Field Using Fracture Analysis”, Geothermal Resources Council, Transactions Vol. 6, 261-264.

Horne, R. N., 1995. ”Modern Well Test Analysis - A Computer Aided Approach”, Petroway Inc., Palo Alto, CA, USA.

Kelly R.T.: “Non-Uniqueness in Well Test Analysis: Case Studies” paper SPE 36528 presented at the 1996 SPE Annual Technical Conference and Exhibition held in Denver, Colorado, U.S.A., 6-9 October 1996.

Lasdon, L. and Waren, A., 1989. GRG2 User's Guide.

Microsoft Excel User's Guide, 1992. Microsoft Corporation, One Microsoft Way, Redmond.

Mishra S. and Ramey H.J. Jr.: “A Comparison of Pressure-Transient and Tracer-Concentration/Time Data for Layered Reservoirs Under Injection,” SPE Formation Evaluation, March 199060-66.

Reiss, H. L., 1980. ”The Reservoir Engineering Aspects of Fractured Formations”, Gulf Publishing Company, Houston, Texas.

Rodriguez, and Horne, R. N., 1983. Geophysical Research Letters, No 10, 289-290.

Sabet A.M., 1991 “Well Test Analysis” Gulf Publishing Co, Houston, TX, USA.