RESERVOIR CHARACTERIZATIONBY TRACER TESTING

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1. INTRODUCTION

Reservoir characterization includes all techniques and methods that improve understanding the geological and petrophysical properties that control the fluid flow. The objective is to provide practical reservoir models for optimum field development.

Tracer study has become an important technique for reservoir characterization, particularly in such specialized areas as geothermal engineering, oil reservoir engineering (Baldwin, 1966), and hydrology (Rubbin and James, 1973). Several processes generally act simultaneously on a chemical constituent while it is transported through a porous medium. Among these, the two primary processes are the physical phenomena of convection and hydrodynamic dispersion. While convection deals with the bulk movement of fluids, hydrodynamic dispersion describes the actions of molecular dispersion and shear or mechanical mixing. These transport processes normally are represented adequately by the well known convection-dispersion diffusion equations with or without chemical reactions. Most of the time, these diffusion equations are based on linear or one dimensional geometry, largely because of the relative ease with which such equations can be solved analytically

Interpretation of tracer tests involve matching tracer data from the field by use of computer simulation programs utilizing aforementioned models. **As** the complexity of the simulator model increases, the number of trial runs needed to'fit field data satisfactorily increases rapidly. The conventional fitting procedure can thus become very cumbersome and can involve prohibitive computer costs. **A** new methodology has been devised to model tests in heterogeneous formations. These rigorous simulators have been replaced by simple response functions generated in a spreadsheet software. Matching the tracer data now involves function evaluations rather than full simulator runs, resulting in a large reduction in computing time.

In this study, six models for the dispersion of a chemical tracer moving through a porous medium were used utilizing a well-known spread sheet software ,Microsoft Excel™. Then these simple models of fluid flow were compared and used to match the results of experimental laboratory tracer tests conducted on fractured reservoir models. The differences between the models were determined and finally, the model parameters were related to reservoir properties.

2. THEORY

The flow of tracer between an injection and a production well pair has been described both analytically and numerically by a number of authors. The governing equation modeling the flow of a tracer is the well known convection-dispersion diffusion equation which can be written in one dimensional form as follows;

$$\frac{\partial C}{\partial t} = -\eta \frac{\partial C}{\partial x} + D_L \frac{\partial^2 C}{\partial x^2} \qquad (1)$$

In this study, six different models were considered : multi fracture model (Fossum and Home 1982), fracture matrix model (OSullivan and Bullivant 1989), uniform porous model (Sauty 1980), double porosity slabs model (OSullivan and Bullivant 1989), double porosity cubes model (OSullivan and Bullivant 1989), and double porosity pseudo steady state model (OSullivan and Bullivant 1989). In each 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 description of each model is given below.

2.1. Multi Fracture Model

This model, as reported by Fossum and Home (1982), assumes a single/multi fracture system,joining the injection and observation wells. Dispersion is due to the high velocity profile across the fracture and molecular diffusion, which moves tracer particles between streamlines (Taylor dispersion). The transfer function C_t is given by the following expression,

$$C_t = \sum_{i=1}^{n} e_i C_r (L_i / u_i, P_{ei}) \qquad (2)$$

where n is number of flow channels in the fracture system, e_i **is** the flow contribution coefficient, L_i is the .apparent fracture length, u_i is the velocity, and P_{ei} is the Peclet number of the i_{th} flow channel Therefore if "n" is taken as one then only a single fracture is present. It should be noted that for all practical purposes, a multi fracture system must be represented with at least two fractures, since it was found during this study that the value of the transfer function, C_t does not change much as n increases.

The form of C_r for each of the paths for a mass of tracer concentrated at point x=0 at time=0 is

$$C_r = \frac{1}{2\sqrt{\frac{t_r}{P_e}}} Exp \frac{-(1-t_r)^2}{\frac{4}{P_e} t_r} \qquad (3)$$

where P_e is the dimensionless Peclet number and t_r is the mean arrival time. Using the above model, by knowing the coefficient of molecular diffusion, D, it is possible to obtain the average velocity, length, mean arrival time, and inferred fracture aperture, b for each flow channel by using the following definition for dispersivity, η.(Rodriguez and Home, 1983)

$$\eta = \frac{2b^2u^2}{105D} \qquad (4)$$

2.2. Fracture Matrix Model

In this model, as reported by OSullivan and Bullivant (1989), there is a large fracture with micro fracturing in the rock matrix on either side. Tracer particles leave the main fracture and enter the micro fracture network (there is a small amount of fluid exchange), stay for a while, and then return to the main fracture. Longitudinal dispersion due to the velocity profile across the fracture is ignored in order to give a clear distinction from the single fracture model. **A** fracture with fluid velocity constant across the thickness and with diffusion perpendicular to the fracture into an infinite porous medium is used in this model. The solution is in the following form;

$$C_r = JU(t-t_b)^{1/2} Exp\frac{-t_b}{w(t-t_b)} \quad (5)$$

Here **U** is the Heaviside step distribution, w is a ratio of transport along the fracture to transport out of the fracture, t_b is the response start time, and J is a model parameter.

2.3. Uniform Porous Model

In the uniform, homogeneous porous model, it is assumed that a slug of tracer is instantaneously injected into a system with constant thickness. It is also assumed that, the flow is rapid allowing the kinematic dispersion components to be predominant. For purely hydrodispersive transfer the solution for one dimensional flow as reported by Sauty (1980) is,

$$C_r = \frac{K}{t_r} Exp(-\frac{P_e}{4t_r}(1-t_r)^2) \quad (6)$$

where

$$K = \sqrt{t_{rm}} Exp(\frac{P_e}{4t_{rm}}(1-t_{rm})^2) \quad (7)$$

$$t_{rm} = \sqrt{1+P_e^{-2}} - P_e^{-1} \quad (8)$$

In the above equations P_e is the dimensionless Peclet number and t_r is the mean arrival time. Similarly, Sauty (1980) also reported an analytical expression for the slug injection of a tracer solution into a two dimensional field on the flow axis as shown below.

$$C_r = \frac{K}{t_r} Exp(-\frac{P_e}{4t_r}(1-t_r)^2) \quad (9)$$

where

$$K = \sqrt{t_{rm}} Exp(\frac{P_e}{4t_{rm}}(1-t_{rm})^2) \quad (10)$$

$$t_{rm} = \sqrt{1+4P_e^{-2}} - 2P_e^{-1} \quad (11)$$

2.4. Double Porosity Slabs Model

The double-porosity slabs model has parallel fractures with constant thickness a, separated by slabs of the rock matrix giving a constant separation b (O'Sullivanand Bullivant, 1989). Tracer movement in slabs is modeled by diffusion perpendicular to the fractures. If the ratio of transport along the fracture to transport out of the fracture, w, the response start time, tb, the matrix block fill up time, t_f, and the model parameter, J, and the injection rate, Q are known, the mass of tracer, m and the ratio of fracture porosity, n_f to matrix porosity n_m can be estimated using the below equation.

$$C_r = JExp(-t_b(2\sqrt{\frac{p}{wt_b}} \tanh(\frac{t_f}{2}\sqrt{\frac{p}{wt_b}}) + p)) \quad (12)$$

Here p is the Laplace transform parameter.

2.5. Double Porosity Cubes Model

In the double-porosity cubes model as reported by OSullivan and Bullivant, (1989), it is assumed that the rock matrix consists of cubic blocks of side b separated by high permeability fractures of thickness a The double-porosity cubes model differs from the double-porosity slabs model because for the cubes the area of the surface a distance b/2+z from the nearest fracture is proportional to the square of z, whereas for the slabs the area of the surface a distance b/2-z from the nearest fracture does not vary with z This affects the way tracer diffuses into the block Tracer movement in the blocks is modeled by diffusion perpendicular to the nearest face The solution is given by the following equation,

$$C_r = JExp(-t_b(2\sqrt{\frac{p}{wt_b}} \coth(\frac{t_f}{2}\sqrt{\frac{p}{wt_b}}) - \frac{4}{t_f} + p)) \quad (13)$$

2.6. Double Porosity Pseudo Steady State Model

For this model, the reservoir contains uniformly distributed high permeability micro fractures which divide the reservoir into low permeability blocks that consist of unswept pores by the fluid flow Similar to the mechanism defined for the fracture-matrix model, the tracer leaves the micro fractures and then returns again However the effect is different, such that the blocks may be filled with tracer Longitudinal dispersion due to the movement of fluid into the micro fracture network is neglected The solution for this case is reported by O'Sullivan and Bullivant (1989) and given below

$$C_r = JExp(-\alpha_m t)U(t-t_b)^{1/2} I_1(2(t_b\alpha_f\alpha_m(t-t_b))^{1/2}) \quad (14)$$

In the above equation α_f is the rate of tracer interchange per unit fracture volume and α_m is the rate of tracer interchange per unit matrix volume.

3. DESCRIPTION OF LABORATORY TESTS

The experimental laboratory tests studied in this work were conducted during 1987 and 1988 and reported in detail by Bayar (1987) and Arpaci (1988). In both of the experimental work, tracer flow in a fractured geothermal model with zero matrix permeability was considered. In the first set of experiments, Arpaci (1988) designed a 3-D fractured model which was composed of *550* marble blocks having three different dimensions. These marble blocks were neither porous nor permeable and the block dimensions were 5x10x5 cm, 5x5x5 cm, and 5x2.5x5 cm. The marble blocks were packed on top of each other regularly **so** that a total of **5** cm fracture spacing was formed. Blocks were packed into a box frame of 50 x 50 x 43cm and pore volume was found as 6600 cc that indicated ***6.6***% fracture porosity as shown in Figure 1.

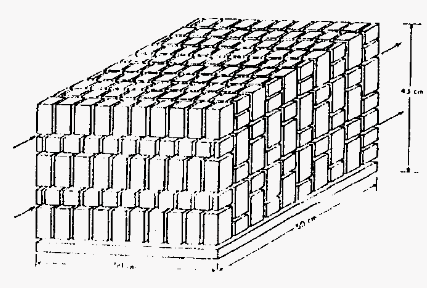

Figure 1.Physical Description of the Fractured 3D Reservoir Model (Arpaci, 1988)

KI solution was used as the chemical tracer and it was injected from the diagonal comer of the model and production concentration of the tracer was monitored from the other end of the diagonal. Injection and production depth was changed to observe the effect of longer path of travel in the fractures. Volume of **KI slug** injected was 1/3 of the pore volume with the concentration of 4000 ppm for each run.

Similar to the previous model, a 3-D fractured model composed of 70 pieces of marble blocks in three different sizes as shown in Figure **2** was built by Bayar (1987). Marble blocks with dimensions 10x10x10cm, 10x10x20cm, and 5x10x20cm were placed freely on top of each other. Similarly 4000 ppm KI solution was selected as tracer solution to be consistent with the aforementioned experimental work. **A** box frame of 60x60x60 was used to cover the fractured medium created and porosity of the medium was determined as **4** % that indicates 5850 cc pore volume. The injection and production scheme was repeated in a similar manner. The experimental runs were named from B1 to B4 and the injection-production scheme was as follows: B1, top-bottom; B2, bottom-top; B3, top-top; B4, bottom-bottom. It should be noted that, when compared to the previous set of experimental design this system was more heterogeneous in nature since the size of the marble blocks were larger than the previous experiments. Therefore, the first set of experiments is expected to behave close to a homogeneous medium.

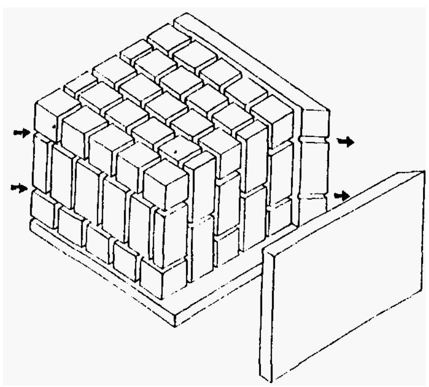

Figure 2. Physical Description of the Fractured 3D Reservoir Model (Bayar, 1987)

4. METHOD OF SOLUTION

The developed analytical models were implemented on a commercially available spreadsheet software (Microsof? Excel™) for convenience. The models were 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 (Microsof? Excel User's Guide, 1992) By minimizing the following objective function R,

$$R = \sum_{i=1}^{n} (C_r - C_{\exp})^2 \qquad (15)$$

the parameters of the proposed analytical transfer finction C_r can be estimated. In nonlinear parameter estimation or curve fitting, it is important to have good initial estimates for the model parameters. 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. 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 the solution process is controlled by defining the solution time, number **of** iterations, and the precision of constraints. 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 finction of noise in the data, as well as the number of data points, and the degree of correlation between the unknowns

5. RESULTS AND DISCUSSIONS

The models were tested for five experimental set of data. Four of them were taken from the set where the system consisted of larger marble blocks (Bayar, 1989) and the fifth one was from the other set. The results are presented as breakthrough curves where effluent concentration is plotted versus time

Figure 3 shows the sum of squares residual for six different models matched to the experimental data. It can be observed that for all the experiments multi fracture model yielded the smallest sum of squares residual. The double porosity models resulted in relatively high residuals compared to other models used.

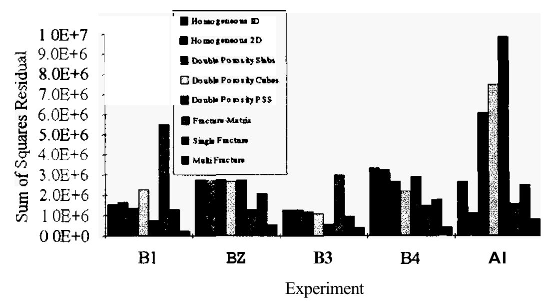

Figure 3. Sum of Squares Residual for Different Models

The analysis results for the aforementioned models are summarized in Tables 1 through 7 and represented schematically in Figures **4** through 8. As it can be seen from the results , for the multi fracture model, for four of the runs where large marble blocks were used, there are secondary fractures yielding high fluid velocity and small mean arrival time. The equivalent aperture of this fracture system is between 9.6 and 13.2 microns. For this flow path Peclet numbers are larger when compared to the shorter main fracture path meaning a convection dominant system. However for the main flow path the fluid velocity and the fracture length **is** relatively small and yields smaller Peclet numbers. It should be noted that the apparent fracture aperture is larger about 30 microns when compared to the secondary flow path. It has been observed that the mean arrival times obtained are in good agreement with the experimental data as it can be observed from the matches to the twin peaked response curves. However for the match to the experimental data where the system is composed of more but smaller marble blocks the observations stated above are reversed. Because of smaller fracture lengths path of travel from injection to production end was larger when compared to run B4 obtained at similar conditions. This reverse behavior can be explained by the fact that the fractured model used is close to a homogeneous porous system since there were much more marble blocks smaller in size when compared to other runs. For this model, the dimensionless parameter e, which can be regarded as a weighing factor, the contribution of the main (first) fracture is more than the secondary fractures. The dispersion coefficients in the **first** fracture system was lower than the secondary fractures, which shows that the loss of tracer to the secondary fractures was more. When compared to the smaller block size model, dispersion was much more pronounced

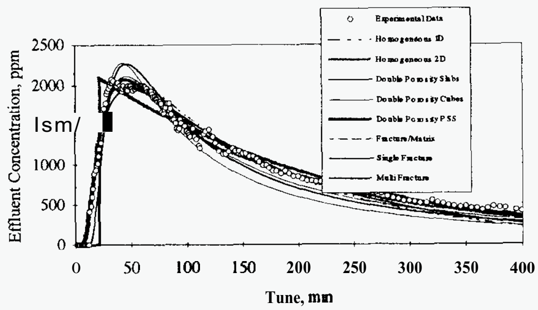

Figure 4. Matches to the Response of Experiment A1.

Table 1. Results of Multi Fracture Model

First Fracture

	P_e dmls	e dmls	u cm/min	L cm	t_m min	η cm²/min	b μm
B1	3.48	1.21	0.71	36.47	51 29	7.64	35.93
B2	10.03	0.39	0.37	36.47	97.60	1.36	29.17
B3	9.96	0.65	0.13	11.03	83.71	0.15	27.11
B4	4.90	0.73	0.39	36.47	94.32	2.88	41.04
A1	3.51	0.67	0.83	168.03	201.95	39.83	70.96

Second Fracture

	P_e dmls	e dmls	u cm/min	L cm	t_m min	η cm²/min	b μm
B1	3049	025	2 11	12895	61 08	8.93	13.24
B2	3469	043	233	12895	5536	8.66	11.82
B3	25 87	0 17	647	178 08	2752	44.55	9.65
B4	3238	033	204	12896	63 15	8.13	13.07
A1	430	144	680	33945	4990	537.05	31.88

If we assume our fractured reservoir can be modeled by a single fracture, there is a distinct difference between the effective dispersion coefficients obtained from the multi fracture model. Dispersion coefficients were ten times greater than the multi fracture dispersion coefficients which is an indication of insignificant molecular diffusion. Mean arrival times and the fracture apertures were in agreement with the previous findings for this case too.

Table 2. Results of Single Fracture Model

	P_e dmls	e dmls	u cm/min	L cm	t_m min	η cm²/min	b μm
B1	5.31	1.38	6.21	339.50	54.68	397.29	30.03
B2	1038	0.85	5.03	339.52	67.48	164.65	23.86
B3	6.79	0.76	4.26	339.54	79.67	213.01	32.04
B4	7.14	1.06	4.40	339.53	77.23	208.96	30.76
A1	1.63	2.13	3.83	339.51	88.62	799.51	69.04

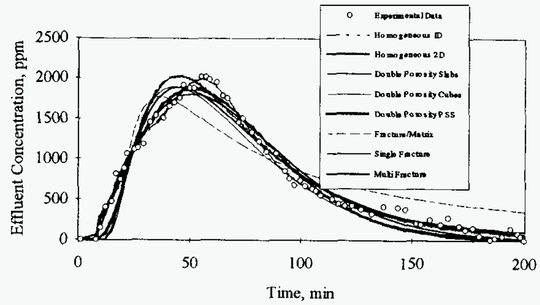

Figure 5 Matches to the Response of Experiment **B**1.

Match between the experimental data and 1D and 2D homogeneous porous models yielded similar results with the exception of last experimental data where the system consisted of smaller marble blocks. For this case 2D homogeneous model resulted in less sum of squares residual which is an indication of better fit. However, the mean arrival time appears to be unrealistic (170.55 min) when compared to the experimental value of 33 min. Moreover, this model resulted in the smallest Peclet number in contrast to other models. In general both homogeneous models resulted in comparable and logical average fluid velocities as well as Peclet numbers and dispersion coefficients.

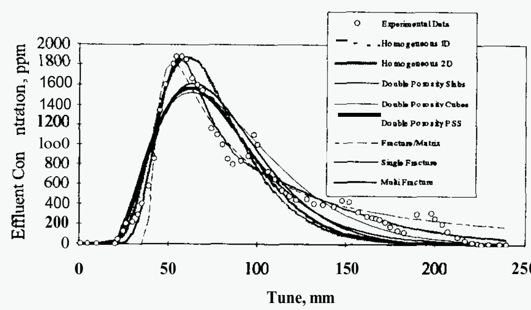

Figure 6. Matches to the Response of Experiment B2.

Table 3. Results of Homogeneous Porous Model

ID	V_x cm/min	η cm²/min	α_l cm	P_e dmls	t_m min
B1	1 3 1	15.89	12.13	5.83	53.97
B2	1.09	5.38	4.93	14.34	64.87
B3	0.89	7.15	8.00	8.84	79.07
B4	0.97	6.44	6.66	10.61	73.22
A1	0.84	34.87	41.37	1.71	83.84

2D	V_x cm/min	η cm²/min	α_l cm	P_e dmls	t_m min
B1	1.11	13.78	12.37	5.72	63.50
B2	1.02	5.09	5.00	14.14	69.52
B3	0.80	6.37	7.94	8.91	88.17
B4	0.88	5.98	6.79	10.41	80.35
AI	0.42	25.46	61.35	1.15	170.57

From the analysis of Fracture/Matrix model results it is possible to obtain only the ratio of transport along the fracture to transport out of the fracture ratio and the mass of tracer entering the stream tube. Two of the experiments (i.e. **B1** and **A1)** showed that transport out of the fracture is more dominant. The mass of tracer entering the stream tube was higher for these experiments when compared to others.

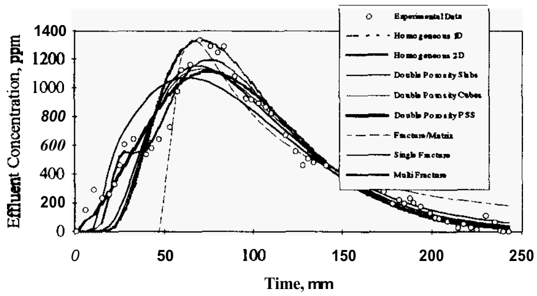

Figure **7.** Matches to the Response of Experiment **B3**

Table **4.** Results of Fracture-Matrix Model

	w	t_b	m
	dmls	min	mgr
B1	**0.21**	**8.61**	**213.10**
B2	**1.32**	**34.22**	**137.17**
B3	1.39	**44.53**	**123.88**
B4	**1.02**	**35.02**	**189.74**
A1	4.05E-6	2.80E-6	**421.11**

From the analysis of the double porosity cubes and slabs models it has been observed that transport out of the fracture is more dominant (w<1) than transport along the fracture for all the cases. Moreover the mass entering the stream tube is in agreement between the models. The ratio of fracture porosity to matrix porosity (n_f/n_m) was small which is an indication of high matrix porosity. However, since the matrix porosity was zero for all the experiments, the results can be considered physically unreasonable. For the double porosity pseudo steady state model, the fracture porosity was found to be greater than the matrix porosity which agrees with the physical situation. Moreover the mass entering to the stream tube is within acceptable limits as well as the sum of squares residual values. The effluent profiles for this case was similar to the uniform porous model curves with the exception of the last set where the system consisted of smaller and more marble blocks. Therefore double porosity pseudo steady state model can be considered the better of the double porosity models.

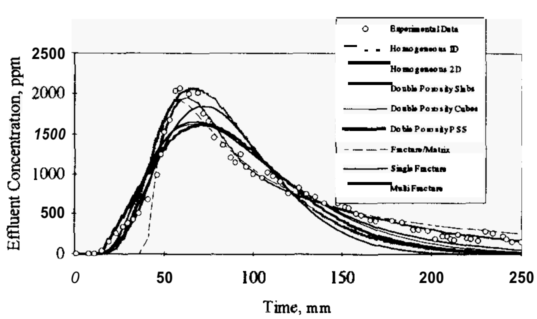

Figure **8** Matches to the Response of Experiment **B4.**

Table **5.** Results of Double Porosity Cubes Model

	w	t_f	t_b	m	n_f/n_m
	dmls	min	min.	mgr.	dmls
B1	**0.12**	**22.39**	**6.83**	**89.61**	**0.11**
B2	**0.10**	**23.01**	**8.98**	**86.64**	**0.12**
B3	**0.08**	**21.20**	**8.00**	**77.10**	**0.09**
B4	**0.07**	**19.46**	**7.29**	**105.98**	**0.08**
A1	**0.15**	**113.49**	7.73	**260.69**	**0.03**

Table **6.** Results of Double Porosity Slabs Model

	w	t_f	t_b	m	n_f/n_m
	dmls	min	min.	mgr.	dmls
B1	**0.32**	**19.89**	**9.81**	**95.93**	**0.16**
B2	**0.42**	**26.34**	**17.07**	**78.54**	0.27
B3	**0.11**	**9.59**	**4.66**	**82.08**	*0.05*
B4	**0.12**	**9.09**	**8.31**	**95.98**	**0.11**
A1	0.10	**130.00**	**6.30**	**393.33**	**0.01**

Table **7.** Results of Double Porosity Pseudo Steady State Model

	w	t_b	n_f/n_m	m
	dmls	min	dmls	mgr
B1	**71.34**	**8.00**	**7.26**	**95.40**
B2	**67.64**	**24.50**	**2.10**	**72.00**
B3	**56.46**	**1.49**	**61.45**	**80.20**
B4	**58.49**	**19.00**	**3.73**	**101.78**
A1	**7.76**	**21.98**	**5.27**	**480.98**

6. CONCLUSIONS

Several models for tracer transport from an injection well to a production well have been developed and matched to the results of laboratory tracer tests conducted on fractured mediums with zero matrix permeability using a least squares approach together with a nonlinear optimization algorithm. In the laboratory tests, injection and production depths were changed to observe injectivity in geothermal systems as well as to observe the effect of longer path of travel in the fractures. Based on the matching results the following conclusions can be done;

The multi fracture model resulted in the smallest sum of squares residual for all the experimental fits. Therefore multi fracture model can be considered as the best model for simulating fast tracer returns in a fractured medium considered here.

The matches for the double porosity models are as good as the fracture/matrix and homogeneous porous models, but a visual inspection of the fits show that the resulting response curves are not similar to the experimental ones. So the results can not be applied directly to systems considered here

Finally, when the results of fracture/matrix model, homogeneous porous models, and single fracture model are considered, it has been observed that all models produce similar and physically reasonable response curves. Although the responses can be considered to be fitting to the experimental data, in the fracture-matrix case the flow is from the fractures and the matrix. Similarly in the homogeneous porous models flow is from the matrix only. Therefore when the nature of the experiments are considered, the results are not physically possible.

This study indicates that if we do not model the physical character of the geothermal reservoir correctly, it is possible to fit several different models that will give unrealistic physical data. Therefore characterization of the reservoir becomes highly important for field development.

7. NOMENCLATURE

b =block size, m.
C_{exp} = experimental concentration, kg m^{-3}
C, = observed concentration, kg m^{-3}
C, =total concentration, kg m^{-3}
D = dispersion coefficient, m^2s^{-1}
e = flow coefficient
I1 = Bessel's function of the 1^{st} kind of order 1
J = model parameter
n_f = fracture porosity
n_m = matrix porosity
p = Laplace transform parameter
P_e = Peclet number
t_b = response start time, s.
t_f = matrix block fill up time, s.
t_r = mean arrival time, s.
u = velocity, ms^{-1}
U() = Heaviside unit step function
w = ratio of transport into the fractures to transport out of the fractures
α_f = rate of tracer interchange per unit fracture volume, s^{-1}
a_r = rate of tracer interchange per unit matrix volume, s^{-1}
η = longitidunal dispersivity, m^2s^{-1}

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