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INTERPRETATION OF THE RETURN PROFILE OF A TRACER TEST IN THE THELAMORK GEOTHERMAL FIELD, ICELAND

I. Kocabas[1], G. Axelsson[2] and G. Bjornsson[2]

[1]SDU
Isparta
Turkey

[2]NEA
Reykjavik
Iceland

ABSTRACT

As a part of a full scale production test, a long term tracer test was performed in the Thelamork low temperature geothermal system, in N-Iceland. The tracer test was aimed at recovering the transport properties of fractures connecting the injection and production wells. Hence, the estimated parameters might be used in determining the performance of the system under various injection schemes. A qualitative evaluation the tracer return profile showed the presence of strong recirculation effects. In addition, the return profile indicated that the medium appears to be highly dispersive.

Earlier modelling studies employed a one-dimensional two path model to match the return profile and substituted the properties of the major path in the Lauwerier model to estimate the thermal breakthrough time. However, the two path model estimates a very large dispersive transport almost equal to the convective transport. This large dispersivity necessitates adding a dispersive heat transport term in the Lauwerier model and as a result reduces the Lauwerier thermal breakthrough time almost to half. Considering the injection and production rates, we used a more accurate one-dimensional five-path model in this work. This model infers a smaller dispersivity and leads to a greater breakthrough time than the two path model, owing to both increased heat transfer area with increasing number of fractures and less dispersive transport of heat.

INTRODUCTION

The tracer test conducted in the Thelamork field was a part of a long term production test and the following is a summary of the information presented in an article[1] on the feasibility of exploiting this field. The Thelamork geothermal field, located about 11 km north of the town of Akureyri in N-Iceland, is a low temperature system. The only manifestation of geothermal activity in the Thelamork area was small hot spring discharging at a rate of 0.3 l/s at 45°C. However, prehistoric hot springs precipitated a significant amount of silica. The field had long been considered for development to serve the space heating of the Akureyri district.

After a decade of geothermal research and following the drilling of a productive well in the summer of 1992, namely Well-11, a feasibility study was started to determine whether exploiting the system would be economical. For this purpose a nine-month full scale production test was carried out. The production test involved producing the new well for nine months and observing the system's response such as production rates, water level changes, and carrying out chemical analyses. Also, a partial reinjection where some of the water produced from Well-11 was reinjected into wells 6 and 8 and two tracer tests where bromide was released into Well-6 and fluorescein was released into Well-8, were performed.

The bromide return profile obtained from the measurements at Well-11 was analyzed and the results were used to estimate the possible reservoir performance under various injection conditions. Hence, a conclusion was sought whether exploiting the field would be economical or not.

The reservoir performance analyses were specifically targeted on predicting future water level changes in the reservoir, reservoir cooling due to infiltration of colder groundwater, and the possibility of heat mining and aiding material balance by reinjection. Among these objectives, heat mining and preserving material balance closely depend on estimating the transport characteristics of flow paths connecting possible injectors and producers. The geothermal reservoirs is believed to be characterized by nearly vertical fractures and/or dykes serving as fast flow paths. The fracture parameters controlling the transport in the reservoir may be determined by tracer transient analyses. Therefore, the tracer test conducted as part of the full scale production test in Thelamork was aimed at identifying possible fast flow paths and their parameters' values and hence aiding the design of a full scale reinjection scheme. Following is a discussion of this partial reinjection and the tracer test.

TRACER TESTING AND PARTIAL REINJECTION AT THELAMORK

Like most geothermal reservoirs, the reservoir at Thelamork is also believed to be distinguished by the presence of vertical fractures and/or dykes. Therefore, drilling of productive well in such fields depends on the ability to intersect such structures. After drilling of five exploration wells that were unsuccessful, Well-11 drilled in the summer of 1992 intersected a major feed zone. During a short period of testing, this well was found to have a great initial productivity. However, in this well and most of the exploration wells a rapid drawdown was also observed.

These findings indicated that Thelamork is in fact a fractured geothermal field and that the hot water flows upward through the highly permeable fractures. Suspecting that the long term productivity of well-11 may be limited, the company started a long term production test. After seven moths of pumping Well-11, some of the produced fluid was reinjected into Wells 6 and 8. When a virtually steady state was reached a known mass of bromide and fluorescein was injected instantaneously into wells 6 and 8, respectively.

Fluid samples taken frequently from Well-11 were analyzed to determine the two tracer concentrations. Then the concentration data was plotted against time to obtain the tracer return profiles. An approximate evaluation of the return profiles stated that almost 60% of the bromide but only 24% of the fluorescein was recovered.

INTERPRETATION OF TRACER RETURN PROFILES

In order to infer the fracture parameters controlling the transport, one needs to perform a quantitative evaluation of the return profiles, which is presented in the following two sections comparatively.

Earlier Studies

In the earlier studies the tracer return profiles were interpreted by using a simple one-dimensional model of tracer transport[1]. In this analysis, first the return profile was corrected for a single recirculation effect and then the corrected profile was matched to a theoretical return profile by nonlinear regression. From the analysis of bromide's return profile for well-6, two flow channels were identified between the injector and the producer. It was found that the smaller channel accounted for 15% of the total transport and the larger one for 85%. From the match of the data with the model produced curve, shown in Fig.1, the estimated parameter values are given in Table 3. The assumption that the fracture has a 1m width and 30% porosity gives a flow channel height of 80m for the well dipole 6-11.

Using these data and assuming a heat depleted geothermal water temperature of 30^0C, one can predict the temperature profile of the outflowing fluid at Well-11. Fig.2 shows these estimated temperature profiles for several injection rates.

In this test, however, as explained in the next section, multiple recirculation took place and the recirculation effect appears to be strong.

Discussion of Earlier Studies

The method of analysis presented in the previous section had several drawbacks. First of all, the employed analysis is applicable for small recirculation effects, which is untrue for this case. Secondly, the model's equation used for matching the tracer return profile is inconsistent with the actual conditions of the test. That equation, known as the resident concentration solution[4], is inappropriate for interpreting a flux concentration profile, especially for highly dispersive systems. The estimated parameter values given in Table 3, show that the dispersive transport is almost equal to the convective transport. Finally, the temperature return profiles were estimated by using the Lauwerier model which ignores the dispersive transport.

Considering the estimated parameter values indicates a highly dispersive transport, one can't ignore the dispersive transport of heat. The only objection to this argument may be questioning the equality of dispersivity of a medium to tracer and heat. This objection is rejected because many field experiments[5] has shown that dispersivities to heat and chemical tracers are indeed of equal order.

The Interpretation Technique Employed in This Work

In any tracer study, prior to applying a quantitative interpretation method a qualitative evaluation of the return profile may reveal valuable pieces of information. A qualitative evaluation of the Thelamork data may be carried out as follows. The observed profile in Fig. 1 for well-6 indicates that there is only one peak and its arrival time is at approximately 9 days. The maximum concentration value is close to 170 ppb and it reduces to a value of 50 ppb after two months. The return profile displays a gentle slope between the peak and the finally observed values. Considering the travel time of the peak is 9 days, one can conclude that the fluid flowing in the main path contributing to the peak concentration must recirculate at least five times in two months. Therefore, there may be a strong recirculation effect on the data.

The most important conclusion is, however, derived from the consideration of injection and production rates. During the tracer test, Well-11 was produced at a rate of 15 l/s, and 4 l/s of fluid is injected into Well-6 and 2 l/s into Well-8 meaning that the concentration of any traced fluid coming from Well-6 and or Well-8 is reduced at least three times upon reaching Well-11. If there were only one major flow path then the peak arrivals should have repeated at the multiples of the first peak arrival time. In addition, the concentration at any peak must have been at least one-third of the previous peak concentration. Consequently, the concentration at about 18 days would have been less than 50 ppb and at about 27 days less than 17 ppb and so on.

Being unable to observe such a profile in Fig.1, and considering the injection and production rates, we may conclude that the tracer return profile in Fig.1 must have been produced by multiple paths, at least four of which are main and the rest are supporting. Therefore, the return profile must be interpreted quantitatively by using the more accurate model of multiple flow paths.

In this work, the tracer return profile was interpreted quantitatively by the solutions corresponding of multiple flow path models, derived in a companion paper[3] in which the theory of recirculating tracer tests is developed. The Laplace space solution representing the transport in a multiple path is:

$$\overline{C}=\left[\left(1-\sum_{j=1}^{N_2} fr_j\overline{C}_{j1}\right)\left(\sum_{i=1}^{N_1} fr_i\overline{C}_{i1}\right)^{-1}-1\right] \qquad (1)$$

where fr_i is the rate fraction in the i^{th} path, C_{i1} is the Laplace space concentration value of the i^{th} path at Well-11, and N_1 and N_2 are number of main and supporting paths respectively. The definitions of the terms indexed by j are the same except that the index j means supporting. Here, the main paths are considered as fractures connecting the injection well where the tracer is initially introduced and the production well, in this case wells 6 and 11. The supporting paths, on the other hand, are the fractures connecting the injection well which receives tracer by recirculation and the production well, namely wells 8 and 11. Thus, according to this equation while the wells 11 and 6 are connected by N_1 paths, wells 11 and 8 are connected by N_2 paths.

Matching the tracer data from well 6 to Eq.1, with N_1=4, and N_2=1shown in Fig.3, yields the parameter values given in Table 4. Fig.3 indicates that the data matches the model profile satisfactorily, except at the last segment. This indicates that possibly there exists another flow path which is longer than the rest. Nevertheless, since the breakthrough is mainly affected by short paths of large capacity, the estimated parameter values could be used for predicting the reservoir performance.

The estimated Peclet number, a measure of dispersive transport to convective one, in the multiple path model are 3.7, 9.2, 4.2 and 6.7 for the four main flow paths. The flow fraction in the third path is 10% and 5% in each of the remaining three paths. These values are an indication of a significant dispersive transport in addition to the convective transport, even though it is much less than the one predicted by the two path single-recirculation model.

As a result, for the reservoir performance calculations the effect of the dispersive transport of heat must be taken into account. A comparison of the reservoir performance prediction by earlier studies and this study will be presented in the following.

PREDICTING RESERVOIR PERFORMANCE UNDER REINJECTION

Assuming that heat may be considered a special type of tracer, one may borrow the tracer transport models presented in detail by Kocabas[2] , for studying the heat transport in fractured media. If the thermal dispersion is ignored, the dimensionless Laplace transformed temperature at Well-11 is:

$$\overline{T}_D = \frac{1}{s} exp\left(-s - \sqrt{s/\theta_2 P_t}\right) \qquad (2)$$

When the thermal dispersion is taken into account, as it should be in this field, the dimensionless Laplace transformed temperature at Well-11 is:

$$\overline{T}_D = \frac{1}{s} exp\left[\left(1 - \sqrt{1 + 4\left(s + \sqrt{s/\theta_2 P_t}\right)}\right)P_e/2\right] \qquad (3)$$

In Equations 2 and 3, the two parameters P_e and P_t are the longitudinal and transverse Peclet numbers. They are defined as:

$$P_e = \frac{t_d}{\theta t_w} \qquad (4)$$

$$P_t = \frac{t_t}{\theta t_w} \qquad (5)$$

where t_d, t_w and t_t are three characteristic times given by:

$$t_d = \frac{\rho_f c_f L^2}{D_t} \qquad (6)$$

$$t_w = \frac{L}{u} \qquad (7)$$

$$t_t = \frac{b^2 \rho_f^2 c_f}{k_m} \qquad (8)$$

and the heat capacity ratios θ and θ_2 are:

$$\theta = \frac{\rho_f c_f}{\phi_f \rho_w c_w} \qquad (9)$$

$$\theta_2 = \frac{\rho_f c_f}{\phi_m \rho_m c_m} \qquad (10)$$

The predicted dimensionless temperature profiles for these two cases are shown in Fig.4. The parameter values used to compute the profiles are written on the figure next to each curve pair. From the parameters, the longitudinal Peclet number was assigned a value such that the thermal dispersivity is equal to the one predicted from the tracer profile interpretation. This assignment is justified by the many field observations reported[5] in literature. Fig. 4 shows that in case of thermal dispersion a significant reduction in the production temperature occurs as much as 4 times earlier than that would be without dispersion. It also shows that at late times, the effect dispersion disappears and the two models' curves coincides.

The thermal fluid and rock properties used to calculate some of the transport parameters are given in Table 1. Based on the flow and transport parameters obtained from the tracer analysis, the dimensionless temperature profile of each path is plotted against the dimensionless time in Fig.5. Using the T_{Df} values corresponding to a t_D of 4 in Fig.5, we can also calculate the dimensionless temperature T_{Dw} produced by a path at the observation well. The temperature likely to be produced by multiple paths is calculated from:

$$T_{Dw} = \sum_{i=1}^{N} fr_i T_{Dfi} \qquad (11)$$

The T_{Dw} values obtained for each approach is given in Table 2. This table shows that in either of the approaches, including the thermal dispersion causes significant increases in T_{Dw} , especially pronounced in the flux concentration, C_{FF} , case. Most importantly, using C_{RR} based parameters yields T_{Dw} values almost 50% greater than those given by C_{FF} based parameters. These results indicates the great benefit in using the more accurate C_{FF} model of multiple recirculation to interpret the tracer return profiles.

CONCLUSIONS

The conclusions derived from the interpretation of the tracer test conducted in the Thelamork field may be listed as follows:

The tracer return profiles displayed a strong recirculation effect and a apparent high dispersivity, indicating that the injectors and the producer are connected by multiple fractures. In cases of tracer test data distinguished by either such features an appropriate solution to the convection dispersion model is necessary. Otherwise, large errors may occur in parameter estimations.

A qualitative evaluation of return profiles may reveal valuable pieces of information, facilitating the quantitative interpretation. The recirculating tracer tests are indeed useful in determining the presence of multiple paths and their transport parameters in case of high dispersion and strong recirculation effects.

For the reservoir performance calculations, including or ignoring the dispersive heat transport makes a significant difference on the thermal breakthrough time estimation. For the Thelamork field, owing to both increased heat transfer area and less dispersive transport of heat, the multiple path model yielded a thermal interference for a specified time much greater than that is given by two-path single recirculation model increasing the fields feasibility for exploitation.

NOMENCLATURE

b = half of fracture width
C = tracer concentration
c = heat capacity
D = thermal longitudinal dispersion coefficient
D_m = diffusion coefficient in the matrix
fr = flow rate fraction of a path
K = mass transfer coefficient
k = thermal conductivity
L = length of a flow path
m = mass of injected tracer
N_1 = number of a main flow paths
N_2 = number of a supporting flow paths
Pe = longitudinal Peclet number
P_t = transverse Peclet number
q = injection or production rate
s = Laplace transform variable
t_d = characteristic time for dispersive transport
t_t = characteristic time for transverse diffusive transport
t_w = characteristic time for convective transport
u = apparent flow velocity
ρ = density
θ = heat storage capacity ratio of fracture to water
θ_2 = heat storage capacity ratio of fracture to matrix

subscripts

D = dimensionless
f = fracture
m = matrix
w = water
i = number of a main path
j = number of a supporting path
l = indicates the concentration value at L
1,2 = indicates parameter of 1st, 2nd, etc. path

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Table 1 Parameter Estimates from Regression Analysis by Single Recirculation Models

mdl	t_{d1}	t_{w1}	P_{e1}	t_{d2}	t_{w2}	P_{e2}	fr_1	fr_2
C_{RR}	17	7.2	2.4	42.4	25.5	1.7	0.11	0.66

Table 2 Parameter Estimates from Regression Analysis by Multiple Recirculation Models

mdl	t_{d1}	t_{w1}	t_{d2}	t_{w2}	t_{d3}	t_{w3}	t_{d4}	t_{w4}	t_{d5}	t_{w5}	fr_1	fr_2	fr_3
C_{3mls}	27	7.7	120	11	173	32	798	3.6	-	-	0.04	0.05	-
C_{4mls}	33	9	119	13	133	32	261	39	179	22	0.05	0.05	0.1

Table 3 Fluid and Rock Properties in the system

ϕ_f	ϕ_m	k_w W/m°C	ρ_w kg/m^3	c_w kJ/kg°C	k_r W/m°C	ρ_r kg/m^3	c_w kJ/kg°C
0.3	0.07	0.677	970	4.2	2.855	2900	0.576

Table 4 Estimated Breakthrough Temperatures for t_D=4

tr. m	th. m	b	$\theta_2 P_t$	P_e	T_{Dfi}	fr_i	T_{Dwi}	T_{Dw}
C_{RR}	md	1 m	0.36	-	0.5	0.17	0.09	0.09
C_{RR}	ad	1 m	0.36	1.5	0.6	0.17	0.1	0.1
C_{FF}	md	0.5 m	0.06	-	0.08	0.1	0.01	0.03
C_{FF}	md	0.5 m	0.09	-	0.18	0.1	0.02	
C_{FF}	ad	0.5 m	0.06	5.0	0.25	0.1	0.03	0.06
C_{FF}	ad	0.5 m	0.09	5.0	0.29	0.1	0.03	

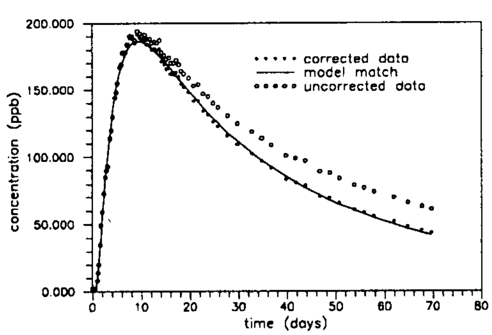

Fig.1 Match of the Tracer Return Profile of the Well Pair 6 and 11, Obtained at Earlier Studies, [after Bjornsson et. al. 1994]

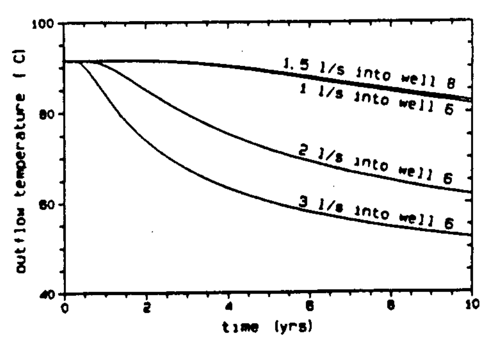

Fig. 2 Estimated Temperature Profiles at Well-11, by Lauwerier Model [After Bjornsson et.al. 1994]

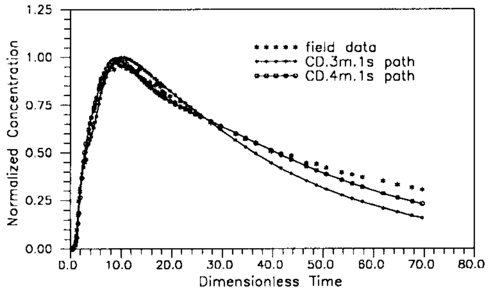

Fig. 3 Matching Tracer Return Profile of the Well Pair 6 and 11, to Four and Five-Path Models

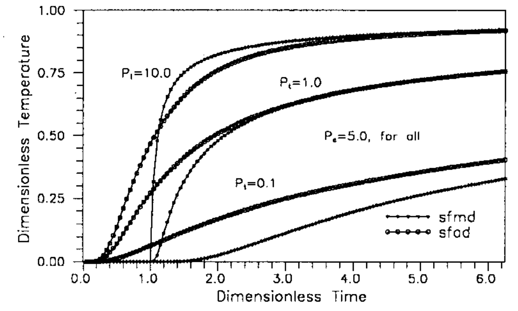

Fig. 4 A Comparison of Theoretical Dimensionless Temperature Return Profiles Predicted by Heat Transport Models Accounting and Ignoring Thermal Dispersion

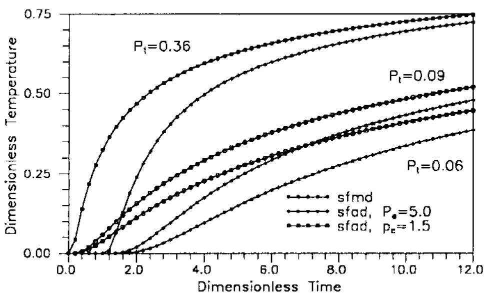

Fig. 5 Possible Dimensionless Temperature Return Profiles for the Thelamork Geothermal Reservoir