NOTICE CONCERNING COPYRIGHT RESTRICTIONS

This document may contain copyrighted materials. These materials have been made available for use in research, teaching, and private study, but may not be used for any commercial purpose. Users may not otherwise copy, reproduce, retransmit, distribute, publish, commercially exploit or otherwise transfer any material.

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specific conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Geothermal Resources Council TRANSACTIONS, Vol. 18, October 1994

BEHAVIORS OF TRACER-CONCENTRATION/TIME CURVES AND APPLICABILITY OF A SIMPLE ANALYSIS METHOD

Michihiro Fukuda[(1)], Ryuichi Itoi[(1)] and Satoshi Akibayashi[(2)]

(1) Faculty of Engineering, Kyushu University, Kasuga City, Japan

(2) Department of Mining Engineering, Akita University, Akita, Japan

ABSTRACT

This paper deals with behaviors of simulated tracer-concentration/time curves of two-well tracer tests for a two flow paths system between wells. The curves exhibit various patterns depending on the Peclet number, the traveling time and the return ratio of injected water of each path. The applicability of a simple method using observed tracer concentration curves to estimate the above parameters according to the behaviors of the simulated curves is also discussed.

INTRODUCTION

Paying special attention to the fact that, in two-well injection-withdrawal tracer tests, for each combination of different values of the Peclet number (Pe) and the flow time of water traveling through a path connecting two wells (a), only one tracer-concentration/time curve combining the first arrival time, $t_{0.01}$ and the peak concentration time, t_m is obtained, the authors have presented a simple method to estimate both Pe and a from $t_{0.01}$ and t_m of an observed concentration curve [Fukuda et al., 1993].

In a case where two or more paths exist between two wells, the tracer transferred through each path flows into the withdrawal well, and consequently, various types of tracer-concentration/time curves may be obtained as the sum of curves with various combinations of the return ratio of injected water, f, the Pe and the a values of each path.

Although even a single peak does not mean that there is only one path between the wells, if two or more peaks are recognizable in a tracer concentration curve, then it is assumed that there are two or more paths. In such a case, the estimation of a_1 and Pe_1 for the first path is made from the first arrival time $t_{0.01,1}$ and the first peak time, $t_{m,1}$. Therefore, to apply this method to such a case, $t_{m,1}$ must not be influenced by the concentration of the second path.

The main purposes of this study are to evaluate the effects of the above parameters on the concentration curves and to investigate the applicability of the method presented in the previous paper to these curves.

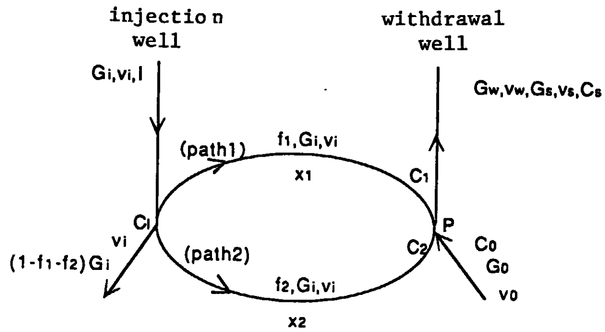

Fig. 1. Conceptual model of tracer return and water flow

CONCEPTUAL MODEL AND TRACER MASS BALANCE

A conceptual flow model similar to the one presented in the previous paper is shown in figure 1. The only difference between this model and the previous one is that the released tracer solution returns to the withdrawal well through two paths, path 1 and path 2, with return ratios of f_1 and f_2, respectively. C_1 and C_2 are the tracer concentrations of the returning solutions at the bottom of the withdrawal well given by substituting first Pe_1 and a_1, and then Pe_2 and a_2 for Pe and a in the following equation:

$$C = C_0 + \frac{C_I - C_0}{2}\Big[\Big\{\mathrm{erfc}\Big(\frac{a-t}{2\sqrt{(a/P_e)t}}\Big) + \exp(P_e) \times \mathrm{erfc}\Big(\frac{a+t}{2\sqrt{(a/P_e)t}}\Big)\Big\} - \Big\{\mathrm{erfc}\Big(\frac{a-(t-t_1)}{2\sqrt{(a/P_e)(t-t_1)}}\Big) + \exp(P_e) \times \mathrm{erfc}\Big(\frac{a+(t-t_1)}{2\sqrt{(a/P_e)(t-t_1)}}\Big)\Big\}\Big] \quad ---(1)$$

where

$$Pe = \frac{u\,x}{D},$$

$$a = \frac{x}{u}$$

and $C_I = C_0 + \frac{I}{G_i v_i t_1} \times 10^3$

The tracer mass balance in the withdrawal well is expressed as:

$$G_w v_w C_s = (f_1 C_1 + f_2 C_2) G_i v_i + G_0 v_0 C_0 \quad --- (2)$$

Considering only the tracer mass transferred through the paths, yields

$$G_w v_w C_s = (f_1 C_1 + f_2 C_2) G_i v_i \quad --- (3)$$

The background tracer concentration, C_0, is dropped in this case and hereafter. Equation (3) can be written in a form of relative concentration as:

$$G_w v_w C_s{}^* = (f_1 C_1{}^* + f_2 C_2{}^*) G_i v_i \quad --- (4)$$

where

$$C_s{}^* = \frac{C_s}{C_1} \qquad C_1{}^* = \frac{C_1}{C_1} \qquad C_2{}^* = \frac{C_2}{C_1}$$

From equation (4), the following equation is finally obtained.

$$\frac{C_s{}^*}{K} = (F C_1{}^* + C_2{}^*) \quad -- (5)$$

where

$$K = \frac{Gi\ vi}{Gw\ vw} f2, \text{and } F = \frac{f1}{f2}$$

SIMULATIONS OF RELATIVE CONCENTRATION CURVES

Using equation (5), model calculations of time versus C_s^*/K are carried out to evaluate the effects of Pe_1, a_1, Pe_2, a_2 and F on the behaviors of the simulated curves. In the calculations, the following values are given to the parameters:

Pe_1, Pe_2 : 5, 10, 20, 50

a_1 , a_2 : 50, 100, 200, 250 ($a_1 < a_2$)

F : 1, 3, 5, 1/5

BEHAVIORS OF SIMULATED CURVES

Some examples of simulation curves are shown in figures 2 to 9, where fine lines and dotted lines represent the first and the second terms of the right side of equation (5), and bold lines are the sum of these two. As seen in the figures, the results of the simulations depend on the combination of values of the parameters and are divided into three categories: curves with two clear peaks, with one peak, and with one clear peak and one swelling. In the last two cases, the tracer transferred through path 2 arrives earlier than the first peak appears.

Effect of Pe on the simulated curve

Figures 2 and 3 show cases where Pe_2 is increased, whereas Pe_1, a_1, a_2 and F are fixed. It is clear from these figures that as the difference between Pe_1 and Pe_2 increases, the summed tracer concentration curve tends to form two peaks instead of one. When two peaks are formed, a part of the curve, from the first arrival time to the first peak time, completely falls on that of path 1 (fine line), which means that the tracer concentration of path 2 does not at all influence either $t_{m,1}$ or $t_{0.01,1}$. It can also be seen that as the difference of the two Pe values increases, the second peak time nearly corresponds to the peak time of path 2, $t_{m,2}$ (dotted line).

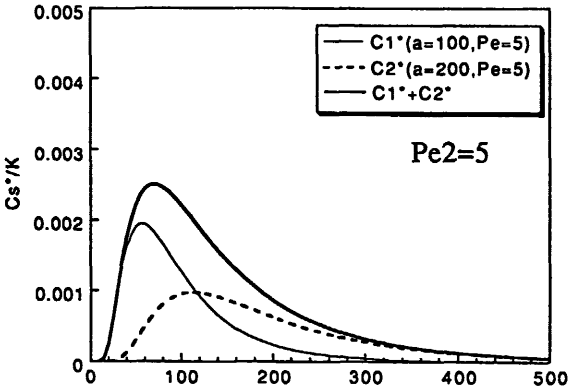

Fig. 2. Time versus C_s^*/K

$t_{m,1} > t_{0.01,2}$

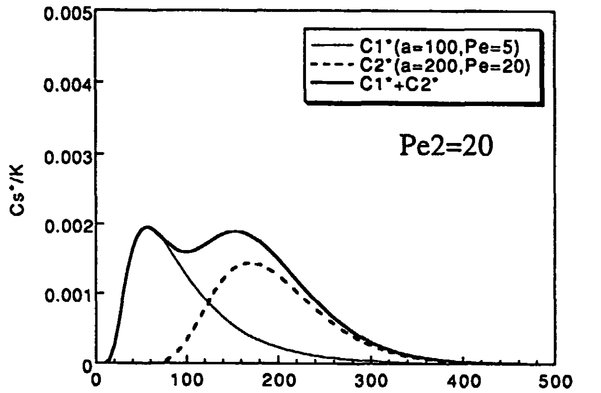

Fig. 3. Time versus C_s^*/K

$t_{m,1} < t_{0.01,2}$

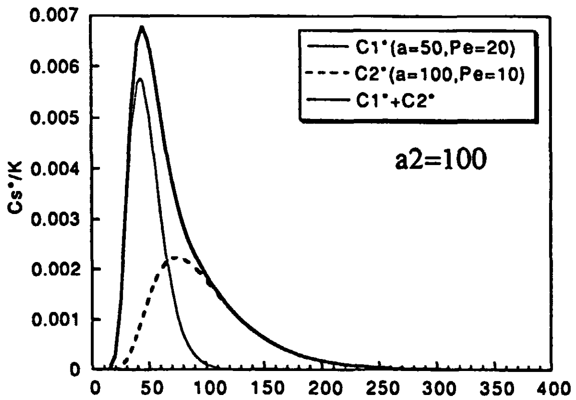

Fig. 4. Time versus C_s^*/K

$t_{m,1} > t_{0.01,2}$

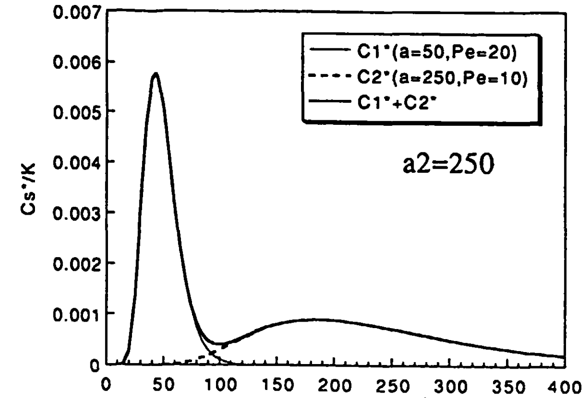

Fig. 5. Time versus C_s^*/K

$t_{m,1} < t_{0.01,2}$

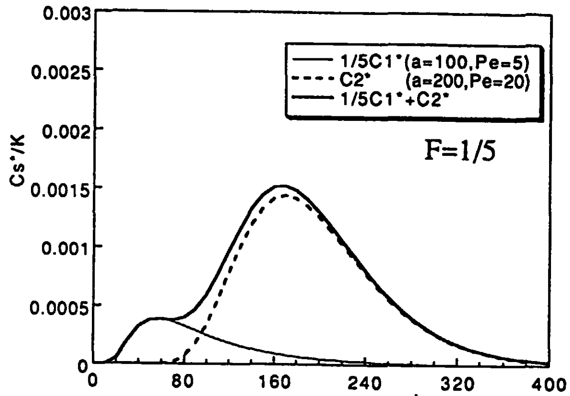

Fig. 7. Time versus C_s^*/K

$t_{m,1} < t_{0.01,2}$

The first concentration is reduced.

Effect of a on the simulated curve

Figures 4 and 5 show simulated curves where a_2 is increased, whereas Pe_1, Pe_2, a_1 and F are fixed. These figures indicate that as the difference between a_1 and a_2 increases, if the second arrival time occurs later than the first peak time, the summed concentration curve tends to form two peaks instead of a single one.

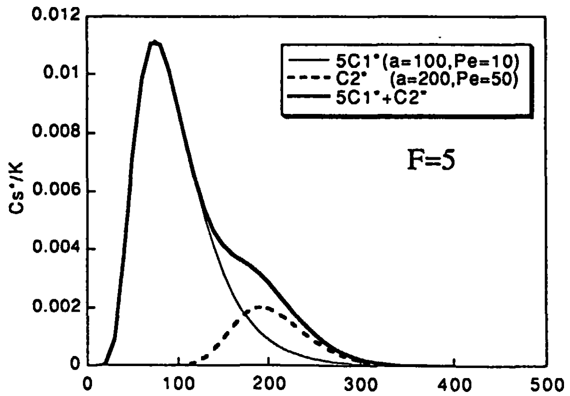

Fig. 6. Time versus C_s^*/K

$t_{m,1} < t_{0.01,2}$

The first concentration is amplified.

Effect of F on the simulated curve

If F is increased, the tracer concentration curves of path 1 are amplified. On the other hand, if F is decreased, the curves of path 1 are reduced, that is, the tracer concentration curves of path 2 are relatively amplified.

Figures 6 and 7 show both the above cases where two peaks are recognizable at F=1: the tracer transferred through path 2 arrives later than the first peak appears. In figure 6, the second peak tends to disappear as the curve of path 1 is amplified. In figure 7, two peaks are maintained : the first arrival time and the first peak time remain unchanged and coincide with those of path 1.

Figures 8 and 9 show cases of one peak at F=1: the tracer through path 2 arrives earlier than the first peak appears. In both cases, the number of peaks remains one. In the amplified case, figure 8, though the peak time of the sum nearly corresponds to that of path 1, they can never coincide in theory, nor can the summed curve fall on the fine line. Similarly, in the reduced case, figure 9, the peak time of the sum nearly corresponds to that of path 2.

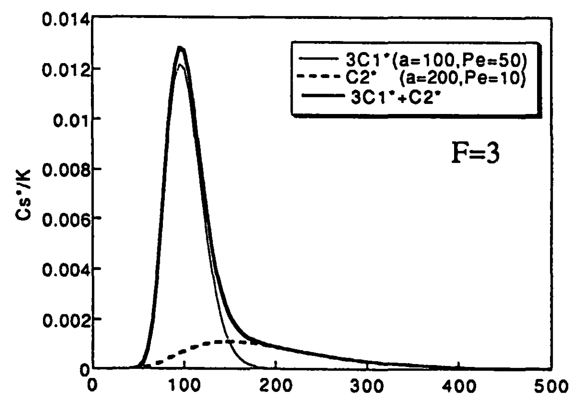

Fig. 8. Time versus C_s^*/K

$t_{m,1} > t_{0.01,2}$

The first concentration is amplified.

DISCUSSION ON THE APPLICABILITY OF THE METHOD

The simple method presented in the previous paper can fairly be applied to curves exhibiting two peaks, corresponding to the number of paths, because the first arrival time, $t_{0.01,1}$ and the peak time, $t_{m,1}$ of path 1 are not influenced at all by the concentration of path 2. In cases where a high amplitude peak is followed by a swelling, the method can sometimes be used, because the first peak time is not influenced by the second arrival time, $t_{0.01,2}$, as in figure 6, but it may, in other cases, as in figure 8, give rise to a slight error. In cases where

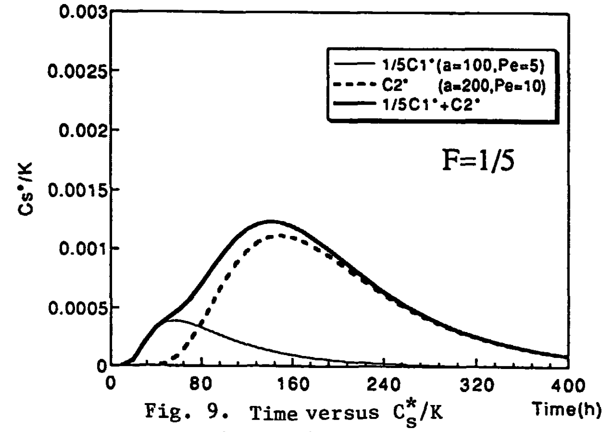

Fig. 9. Time versus C_s^*/K

$t_{m,1} > t_{0.01,2}$

The first concentration is reduced.

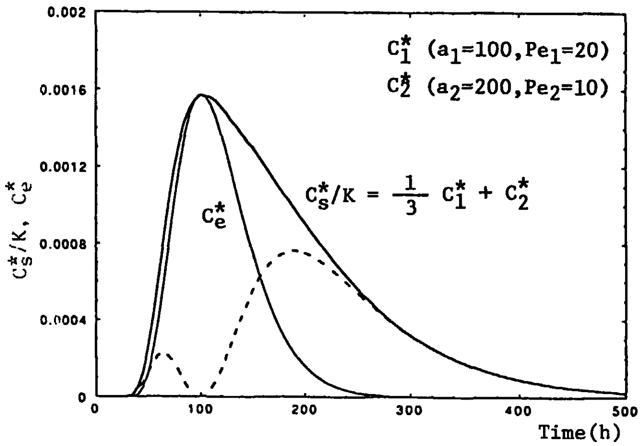

Fig.10. An example of inconclusive analysis: Pe=19.5 and a=116 are estimated instead of the given Pe_1, a_1, Pe_2 and a_2.

a swelling is recognizable ahead of a high amplitude peak, as in figure 9, the method cannot be applied because the second arrival time, $t_{0.01,2}$, is not clear, nor does the peak time of the observed curve coincide with that of path 2.

In cases where there is only one clear peak on observed curves, one path is naturally assumed. However, curves exhibiting one peak are occasionally obtained even in two-path cases, like those shown in figures 2 and 4. This type of curve cannot be analyzed: if an attempt is made, obviously wrong Pe and a are estimated, and strange residues, which cannot be explained, are obtained. Figure 10 shows a typical example, where the dotted line represents the residues obtained by subtracting a tracer concentration calculated from estimated Pe and a.

CONCLUSIONS

From the results of the calculations carried out in this paper, the following conclusions can be reached: the tracer concentration curves vary depending on the combinations of Pe, a, and the return ratio of injected water of each path. The curves can be divided into three categories: with two clear peaks corresponding to the same number of assumed paths, with one clear peak with a swelling, or a single clear peak. The simple analysis method to estimate Pe and a presented in the previous paper is fairly applicable to the first type, occasionally applicable to the second type, but not applicable to the third one. As it is practically impossible to predict the number of paths connecting two wells and to estimate Pe and a immediately from an observed tracer concentration curve, the analysis has to be repeated for each peak, starting from the first one.

Although, in this study, a two-path system was considered, the basic method described above may be extended to systems including several paths.

NOMENCLATURE

a : water traveling time (=x/u) [h]
C : observed tracer concentration [mg/l]
C_I: tracer concentration of released solution [mg/l]
C_0: background tracer concentration [mg/l]
C_s: tracer concentration observed at surface of withdrawal well [mg/l]
D : coefficient of hydrodynamic dispersion [m^2/h]
F : f_2/f_1(ratio of return ratie)
Gi: flow rate of injected water [kg/h]
Gs: flow rate of withdrawn steam [kg/h]
Gw: flow rate of withdrawn water [kg/h]
I : amount of tracer injected [kg]
Pe: Peclet number (=ux/u)
t : time [h]
t_1: time spent to inject tracer [h]
u : water flow velocity [m/h]
vi: specific volume of injected water [m^3/kg]
v_s: specific volume of withdrawn steam [m^3/kg]
v_w: specific volume of withdrawn water [m^3/kg]
x : average water traveling distance [m]

REFERENCE

Fukuda, M., R. Itoi and S. Akibayashi, A simple method to analyze tracer test data, Geothermal Resources Council Transactions, Volume 17,487, 1993.