PROCEEDINGS, Sixteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 23-25, 1991
SGP-TR-134

Modifications to TOUGH and Analysis of Build-up Data of PTS (Pressure/Temperature/Spinner) Logging in a Two-phase Condition

Okabe, T., Osato, K. and Takasugi, S.

Department of Technology, Geothermal Energy Research and Development Co., Ltd., 11-7, Kabuto-cho, Nihonbashi, Chuo-ku, Tokyo 103, Japan

Abstract

The original version of TOUGH(Pruess, 1987) requires a large amount of CPU time for large 2D or 3D problems. This has prevented us from using the original TOUGH on several actual field simulations. Therefore, we have modified the original TOUGH to make less CPU time and allow us to use new TOUGH on large problems. For reducing the CPU time, two new matrix inversion methods were implemented on the original TOUGH.

In this report, first we summarize new matrix inversion method implemented in new TOUGH and second we show inspection results of the accuracy and improvements of speed, and then we show the case study results. Before conducting this case study, the porous medium model for the case study is optimized. As the case study we tried to analyze build-up data acquired by PTS (Pressure/Temperature/Spinner) logging in a two-phase condition. We have been successful in obtaining a good match to PTS data.

1. Introduction

1-1. Modifications to TOUGH

Modifications to TOUGH were done in cooperation with the New Zealand Department of Scientific and Industrial Research(DSIR) (White, 1990). The aims of the modifications are

- to reduce CPU time needed to solve problems and
- increase the number of elements that could be included in TOUGH simulations.

These aims were motivated by the desire to perform the actual field simulation described later in this report. For achieving these aims, two new matrix inversion methods were made available in new TOUGH. One method is a direct one to solve Jacobian matrix for 1D problems such as a single layer and radial flow problem, and the other is a modified Successive Over Relaxation(SOR) method, intended for use on 2D and 3D problems with a large number of elements.

As assessment of new TOUGH, two aspects have been assessed, the accuracy and the speed improvement. To inspect the accuracy, Garg's model as specified in the TOUGH user's guide was used. And to inspect the speed improvement, 1D, 2D and 3D model were used.

1-2. Analysis of Build-up Data

Build-up data are obtained from either PTS logging or pressure monitoring, in most cases. For analysis of build-up data, in the single-phase case, we can use pressure transient test analysis software such as "Multi-Rate Multi-Well" simulator(Schroeder et al., 1984). The assumptions made in this kind of simulator are that the reservoir is unbounded (no closed or constant pressure boundaries laterally), isotropic (flow independent of direction) and confined above and below (no leakage). Since we use an "Early Time Analysis" option, the reliability of the results is excellent. If two-phase conditions occur in the reservoir, it is necessary to use a reservoir simulator like TOUGH. We also found that the wellbore simulator(for instance,Miller, 1984) is useful in both single-phase and two-phase cases.

Before analyzing build-up data, the model for new TOUGH was optimized. The model assumes 1D radial flow, and includes the well block. Optimization involved the construction of fine grids near the well, and consideration of the build-up response. And we tried to match with the actual PTS data obtained by PTS logging in Japan.

2. Modifications to TOUGH, and Assessment

2-1. Modifications to TOUGH

We ran the original TOUGH under a profiler to detect the areas of the code that would most benefit from modification. As a result, in case of problems with a few elements(ex. 1D model) almost 70 % of the CPU time is spent calculating thermodynamic properties of water and steam and in case of problems with large number of connections between elements(ex. 2D or 3D model) almost 80 % of the CPU time is spent on matrix inversion. Here regarding numerical equation solved by TOUGH, the mass and energy balance equations(1) can be discretized in space using the integral finite difference method and time derivatives are approximated using a fully implicit first rder method. Then the mass and energy balance equations can be reduced to a set of nonlinear algebraic equations(2).

$$\frac{t}{dt}\int_{V_n} M^{(\kappa)} dv = \int_{\Gamma_n} F^{(\kappa)} \cdot n \, d\Gamma + \int_{V_n} q^{(\kappa)} dv \qquad (1)$$

where

V_n : an arbitrary flow domain

Γ_n : area of V_n

$M^{(\kappa)}$: a volume-normalized extensive amount of component κ per unit volume

$F^{(\kappa)}$: flux of component κ

$q^{(\kappa)}$: sink and source of component κ per unit volume

κ : water, air, heat

$$R_n^{(\kappa)k+1} \equiv M_n^{(\kappa)k+1} - M_n^{(\kappa)k} - \frac{\Delta t}{V_n}\{\Sigma A_{nm} F_{nm}^{(\kappa)k+1} + V_n q_n^{(\kappa)k+1}\} \qquad (2)$$

where

$R^{(\kappa)k+1}$: residual form

A_{nm} : interface areas

$F_{nm}^{(\kappa)k+1}$: flux of component κ

The subscripts(nm) mean that the respective quantities are to be evaluated at the interface between volume elements n and m.

k labels the time step and $\Delta t = t^{k+1} - t^k$.

Above-mentioned equations are presented in more detail in the TOUGH user's guide.

For a system that has N grid blocks that is a set of nonlinear equations in the 3N primary variables. Because for each volume element there are three primary variables(Single-phase: Pressure, Temperature, Air mass fraction ; Two-phase: Pressure, Gas saturation, Temperature). To solve nonlinear equations we perform Newton Raphson iteration.

Denoting the primary variables at time k+1 as $x_1 \cdots x_{3N}$ the Newton Raphson iteration is

$$x^{i+1} = x^i - J^{-1} R^{k+1}(x^i) \qquad (3)$$

J is the Jacobian matrix of the system $J = \partial R_i^{i+1} / \partial x_i$

This 3N*3N sparse Jacobian matrix dominates the CPU time for most problems. This matrix inversion is normally done using the Gaussian elimination. But by exploiting properties of the matrices, the CPU time to solve problems becomes faster than the Gaussian elimination. Then we have made available two new matrix inversions to it. One is a generalized Thomas algorithm for tri-diagonal matrices which is only applicable for 1D problems. The other is an iterative method to solve (3). Figure 1. shows the typical structure of Jacobian matrices for 1, 2 and 3D problems.

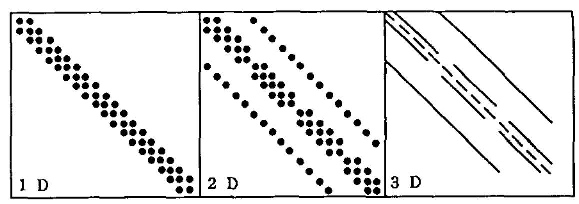

Figure 1. Some different structures

In order to use an iterative solution technique for (3), we used a modified Successive Over Relaxation(SOR) method. If J = D - U - L, the conventional SOR method to solve the problem Jx = R is defined as

$$(D - \omega L) x^{m+1} = ((1-\omega) D + \omega U) x^m + R) \qquad (4)$$

where

D : diagonal mtrix

U : strictly upper triangular matrix

L : strictly lower triangular matrix

As equation (4) is not suitable for Jacobian matrices generated by TOUGH, there is no guarantee that at all the diagonal elements are non zero. As a counter-measure, the equation (4) is modified to premultiply (4) by the inverse of the block diagonal matrix formed from the 3*3 matrices on the diagonal J.

$$(I-\omega L')\,x^{m+1}=((1-\omega)\,I+\omega U')\,x^{m}+R' \qquad (5)$$

The matrix

$$\mathcal{L}\omega=(I-\omega L')^{-1}((1-\omega)\,I+\omega U') \qquad (6)$$

is called the point Successive Over Relaxation matrix.

And optimum omega value is given below.

$$\omega=2/(1+\sqrt{1-\mu^{2}}) \qquad (7)$$

μ is the largest eigenvalue of (L'+U') which is accompanied with property A matrix(which is referred by Young, 1954). A matrix with this property can be transformed by a permutation matrix and thus transformed Jacobian matrix is shown in Figure 2. for example. But if this Jacobian matrix does not have the property A, it may be fail to converge. And also it may be problem that the cases are consist of polygonal elements because one may not be able to transform in this way.

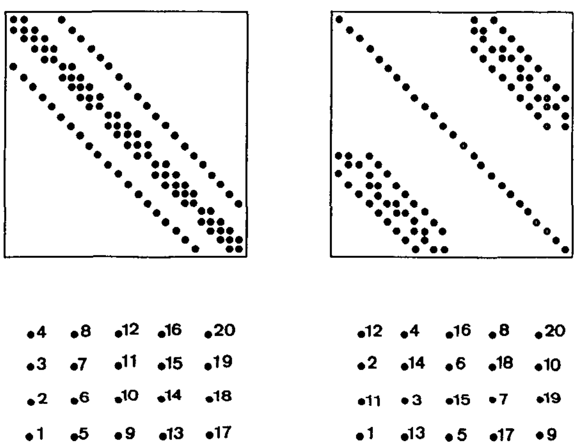

Figure 2. Permutations of the Jacobian Matrix for 2D Problem

As a further work, SUPST and COWAT in the code for thermodynamic routines were rewritten to remove all unnecessary array references and many of the large exponentiation. Consequently SUPST and COWAT was 40 - 70 % faster than the original.

2-2. Assessment of new TOUGH

(1) Accuracy

To verify accuracy, Garg's model as specified in the TOUGH user's guide was used. Figure 3.(a) shows the results of this calculation. New and original TOUGH are in good agreement with each other, and also match Garg's semi-analytical theory. The new TOUGH was 1.9 times faster than original TOUGH.

In the 1980 Stanford Geothermal Workshop, there was a DOE comparison of existing geothermal simulators and analytical solutions. We have compared new TOUGH with these reported results. Figure 3.(b) shows the results of this comparison in enthalpy, for two-phase radial flow in a porous medium.

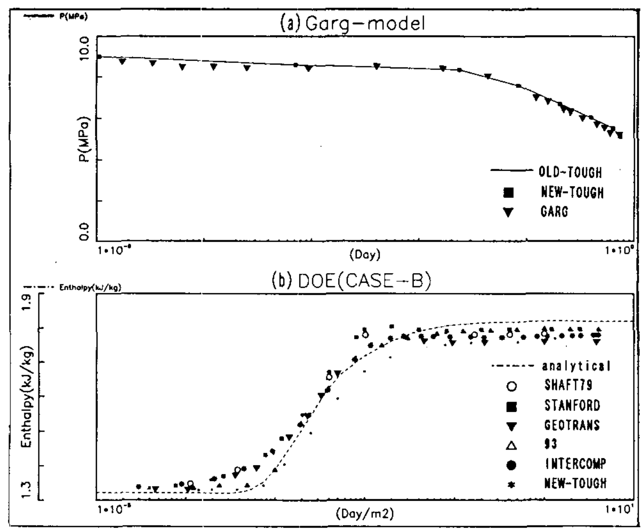

Figure 3. Comparison of NEW TOUGH with Garg's Model and DOE (Case-B)

(2) Speed

A comparison of CPU time is shown in Table-1. A speed improvement is observed, with simulations being 1.9 times faster for the 1D problem, 1.5 times faster for 2D problem and 23 times faster for 3D problem. The nature of the problems simulated is indicated in Table-1.

Table-1. Comparison of CPU Time

Dimension	Elements	Connections	CPU Time (sec)			Remarks
			Original	New	Ratio	
1 D	50	49	215.9	114.4	1.89	Garg's Model
2 D	164	289	348.4	224.3	1.55	2D Infiltration Problem
3 D	196	459	2076.6	89.9	23.10	Cubic Model

3. Analysis of Build-up Data of PTS Logging in a Two-phase condition

3-1. PTS Data and Analysis

PTS logging has been available for five years, and has been used in many geothermal regions in Japan. The quality of PTS data is excellent, and the analysis of such data is very useful for reservoir evaluation. Methods for analyzing PTS data are mentioned in Introduction.

3-2. Optimization of the Model

Before running the case study we optimized the grid used to model the area surrounding the well.

We assume radial flow in a uniform porous medium towards a well of radius 0.2 meters.

The initial grid consisted of a well block, 500 equal thickness(1 meter) cylindrical blocks followed by 100 elements of gradually increasing thickness.

This grid was optimized in the following way.

(1) Calculation of drawdown and confirmation of boiling front

Using the initial grid, pressure drawdown was calculated and the presence of a boiling front was confirmed. The grid was then refined out as the boiling front and the calculation repeated.

Figure-4a and -4b show pressure and temperature curves after 20 days production for various block thickness. As can be seen the boiling front lies between 1.75 and 2 meters from the well block.

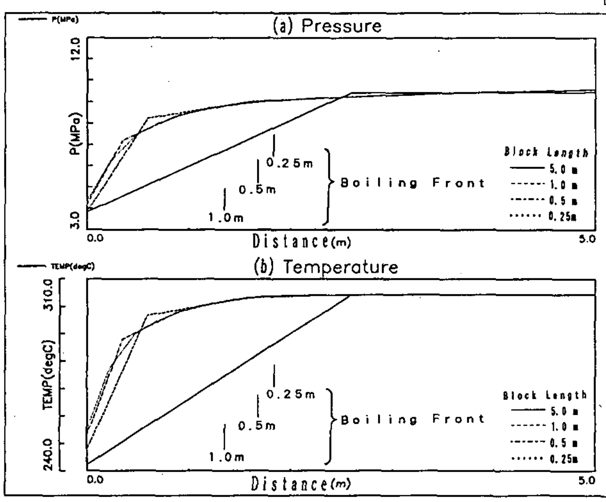

Figure 4. Draw-Down Curves for Various Block Length

Refining the grid around the well smooths the curves out to the boiling front but has little effect past the front.

The temperature and pressure calculated using the finest grid were used as initial conditions for the pressure build-up calculation.

(2) Calculation pressure and temperature build-up, and confirmation of convergence

Figure 5. shows pressure and temperature curves for various block sizes 8,000 seconds after well shutdown. As block size is reduced these curves converge to a limit. It is apparent from these curves that there is little benefit in reducing the block size below 0.5 meters.

Then 0.5 meters block size model is used as an optimized model for the case study.

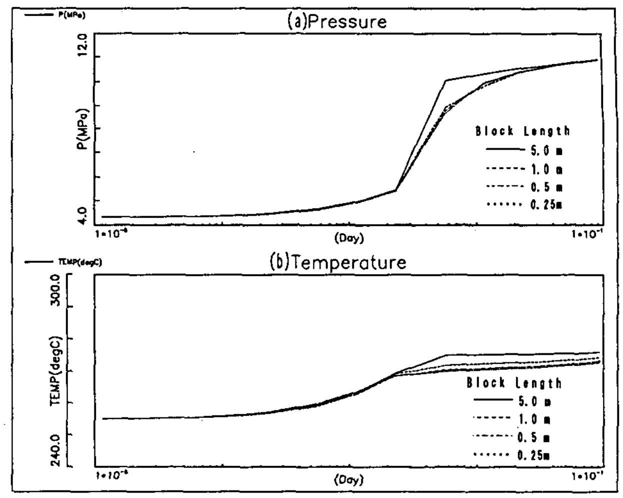

Figure 5. Build-up Curves for Various Block Length

3-3. Case Study

Data used in this case study was acquired by PTS logging in Japan. At that time the well was in a two-phase condition and flashing was in the formation. Before shutdown the pressure and temperature at the main feed point were 3.4 MPa and 237.4 deg. C respectively, and flow rate was 13.94 kg/s. After shutdown we recorded PTS data at the feed point in the well for about 2 hours.

In this time the pressure recovered to 6.2 MPa and temperature to 271.9 deg. C. Figure 6. shows the matching curves.

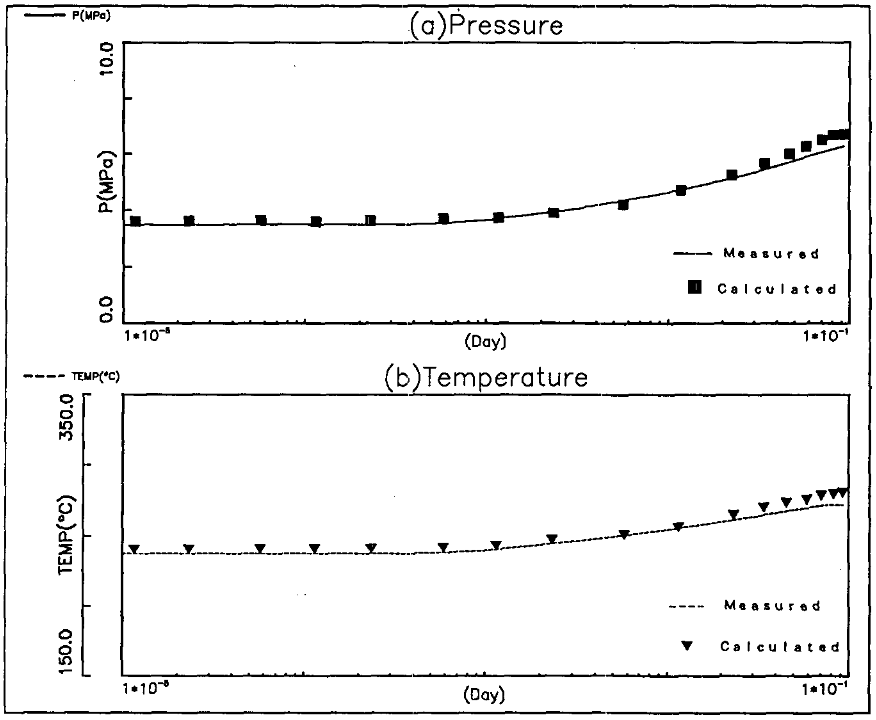

Figure 6. Matching Curves for Pressure and Temperature

4. Conclusions and Future Research

We drew following conclusions from the work described in this report.

(1) The modified SOR method for 2D and 3D problems, Thomas algorithm for 1D problems made the CPU time less required and made us possible to handle with larger problem.

We confirmed the speed-up and the accuracy of new TOUGH. The speed improvement was most excellent for 3D problems. For instance, new TOUGH was 23 times faster than original one.

(2) Grids for the case study were optimized using a uniform porous medium model. Then, we tried to match this PTS data and could have a good agreement.

As a future research, we will try to match this PTS data using double porosity model.

5. References

Young, D. (1954): Iterative Methods for Solving Partial Differential equations of elliptic type, Trans. Amer. Math. Soc.

Varga, R. S. (1962): Matrix Iterative Analysis, London, Prentce-Hall International. New Jersey, Prentice-Hall.

Wachspress, E. L. (1966): Iterative Solution of Elliptic System, London, Prentice-Hall, Inc.

Miller, C.W. (1979): Numerical Model of Transient Two-phase Flow in Wellbore, LBL-9056

Stanford Geothermal Program(SGP) (1981): Proceedings of the Special Panel on Geothermal Model Intercomparison Study, Rep. SGP-TR-42. Stanford University, Stanford, California.

Schroeder, R.C. and Miller, C.W. (1984): User Guide for MRMW- PC, BG Software, Oakland, California

Pruess, K. (1987): TOUGH USER'S GUIDE, LBL-20700.

White, S. (1990): Speeding Up TOUGH, TOUGH Workshop, LBL, California.

Okabe, T., Osato, K. and Takasugi, S. (1990): Case Study Using Faster TOUGH, TOUGH Workshop, LBL, California.