

PREDICTION OF EFFECTS OF HYDRAULIC FRACTURING
USING RESERVOIR AND WELL FLOW SIMULATION

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ABSTRACT

This paper presents a method to predict and evaluate effects of hydraulic fracturing jobs by using reservoir and well flow numerical simulation. The concept of the method is that steam production rate at the operating well head pressure is predicted with different fracture conditions which would be attained by the hydraulic fracturing jobs. Then, the effects of the hydraulic fracturing is evaluated by comparing the predicted steam production rate and that before the hydraulic fracturing. This course of analysis will suggest how large fracture should be created by the fracturing job to attain large enough increase in steam production at the operating condition and the best scheme of the hydraulic fracturing job.

INTRODUCTION

This study was carried out in the project Technology for Increasing Geothermal Energy Recovery (TIGER) (Yokoi et al., 1989) assigned to Geothermal Energy Research and Development Co., Ltd. by New Energy and Industrial Technology Development Organization.

To increase steam production of geothermal wells, hydraulic fracturing jobs are commonly applied (e.g., Katagiri et al., 1980; Katagiri and Ott, 1983). However, it was sometimes not possible to attain large enough increase in steam production by the hydraulic fracturing. This suggests that plans and procedures of hydraulic fracturing jobs are very important to attain good results. This also suggests that it is important to quantitatively predict effects of the fracturing job and to evaluate how large fracture should be created in advance of the fracturing job to establish the best fracturing scheme. This study is motivated by this reason. The purpose of this study is as follows:

1) To develop a method to quantitatively predict effects of hydraulic fracturing jobs.

2) To develop a method to quantitatively compare hydraulic fracturing schemes each other from an economical point of view.

3) To develop a method to establish a quantitative target for hydraulic fracturing jobs to attain.

In this study, we employed reservoir and well flow numerical simulation to predict effects of different fracture conditions which would be attained by different fracturing jobs, and quantitatively studied how steam production of wells of different fractures differ at operating condition. In this paper, we describe the method and some results of the simulation study.

CONCEPT OF THE METHOD

A flow chart of the method is shown in Fig. 1. This method consists of a numerical simulation of fracture propagation under various hydraulic fracturing conditions, a conversion of fracture parameters into permeability and other parameters for numerical simulation grids, and prediction and evaluation of steam production at operating well head pressure using a reservoir and well flow simulator. This course of study would be continued by modifying fracturing parameters until feasible fracturing scheme is found. In this paper, we concentrate on the second and the third items. The first item, the numerical simulation of fracture propagation, is in progress as another part of the TIGER project.

CONVERSION OF FRACTURE WIDTH INTO GRID BLOCK PERMEABILITY

The Cubic Law is commonly applied to convert fracture width into fracture permeability (e.g., Snow, 1968;

Witherspoon et al., 1979). The Cubic Law assumes laminar flow in the fracture. Ignoring the effects of turbulent flow, we employed this Cubic Law in this study, which is written in the following form:

$$k = w^2/12 \quad (1)$$

where, k is the fracture permeability (m^2), w is the fracture width (m). To convert this fracture permeability into grid block permeability, we adopted the concept of Equivalent Porous Media (e.g., Gale, 1982). It is written in the following form:

$$k_1 \cdot w_1 = k_2 \cdot w_2 \quad (2)$$

where, k_1 is the fracture permeability (m^2), w_1 is the fracture width (m), k_2 is the grid block permeability (m^2), w_2 is the grid block width (m).

EVALUATION OF WELL PRODUCTIVITY

In most geothermal power plants, wells are operated to maintain its well head pressure to feed the turbine with steam of the specified pressure. Therefore the evaluation of steam production rate at the operating well head pressure is important from an industrial point of view (Hanano et al., 1990).

Behavior of geothermal reservoir/well system in production consists of reservoir draw down, in-flow performance and ascending flow in the well (e.g., Gudmundsson and Marcou, 1986). Thus, it is necessary to analyze these three behaviors to evaluate steam production rate at the operating well head pressure (Hanano et al., 1990). Therefore, the reservoir simulator is used to analyze reservoir draw down and in-flow draw down, and the well flow simulator is used for ascending flow and two-phase flow in the well.

A flow chart of this evaluation is shown in Fig. 2. To evaluate the change of well productivity at the operating condition, reservoir simulation is carried out to estimate temperature and pressure distribution. Then the steam production rate is evaluated by the well flow simulation using the temperature and pressure at the feed zone. And then, the reservoir simulation is carried out again using the production rate evaluated by the well flow simulation. Through this course of analysis, change of steam production rate at the operating condition is obtained.

DESCRIPTION OF SOME EXAMPLE RUNS

To improve the understanding of the

method described above and to investigate the relation between the well productivity and fracture parameters, some example simulations were conducted. In these example runs, two porous reservoir models, a horizontal fracture model and a vertical fracture model, were employed. Porous models were chosen because it was possible to account for fracture domain by reducing the grid block size around the fracture. Also finely grided porous models can provide better understanding of the flow around the fracture.

Grid geometries of the models are shown in Figs 3 and 4. The horizontal fracture model is the vertical cross sectional model of two-dimensional radial flow (Fig. 3), and the vertical fracture model is a quarter of the three dimensional Cartesian model (Fig. 4). These reservoir models account for both reservoir draw down and in-flow draw down, with fine grids around well blocks and with relatively coarse grids away from the well blocks. Using these models, effects of various fracture length, fracture width and fracture height on steam production at the operating condition were investigated.

Simulation parameters are shown in Table 1. Matrix permeability, porosity, rock heat capacity were referred from typical values used in our field analysis. Also fracture widths estimated from our field data were used. The reservoir simulator is a fully implicit finite difference model which is equivalent to that of Coats (1977). The well flow simulator is the one described by Takahashi (1988).

RESULTS AND DISCUSSION

Change of steam production rate at constant well head pressure of 0.65MPa of the horizontal fracture model is shown in Fig. 5. This result implies that:

1) As soon as the production started, reservoir pressure starts to draw down quickly. This cause the quick decrease in steam production rate shown in Fig. 5. But the draw down of reservoir pressure slows down after a while, resulting from a pressure gradient created in the reservoir. Thus the decrease in steam production rate slows down and approaches to quasi-steady state (Fig. 5).

2) Longer fracture length gives larger steam production (Fig. 5). This is because longer fracture length gives

the larger fracture surface area resulting in smaller flow resistance between fracture and matrix.

Since the steam production at the well head approaches quasi-steady state after approximately 1000 days of production (Fig.5), we use these values for further discussion.

Differences in steam production with different fracture length and fracture block width are shown in Fig.6. This result implies that:

1) Longer fracture length gives larger steam production, however its increase becomes saturated with longer fracture length. This is because larger flow rates in the fracture accelerates the flow resistance around the well bore resulting in larger pressure draw down around the well.

2) Wider fracture block width gives larger steam production, however their maximum steam production rates are different. This is because wider fracture block gives smaller flow resistance, but its effect also saturates as the block width becomes wider.

These results imply that the steam productivity of wells is controlled by combination of fracture length and fracture width. Thus, fracture block volume was chosen to investigate relationship between fracture dimension and steam productivity of wells. The fracture block volume is mostly proportional to amount of fluid injected for the hydraulic fracturing. Steam productivity of various fracture block volume of both the horizontal fracture model and vertical fracture model is shown in Fig.7. This result implies that:

1) Larger fracture block volume gives larger steam production, because of larger fracture surface area and/or thick fracture block width.

2) Steam productions are different at the same fracture block volume if the fracture width or fracture height is different. There is a combination of fracture length and fracture width (height) to give the maximum steam production. This relation is shown as thick solid lines in Fig.7. The best combination is the case of larger fracture width when the fracture length is long, and that of narrower fracture width when the fracture length is short. This indicates that fracture length and width have different effect on steam production and they affect each other independently as discussed

above.

3) The vertical fracture gives larger steam production than the horizontal fracture does even if the fracture block volumes are the same, because of the difference in flow resistance; the flow in the vertical fracture is linear but the flow in the horizontal fracture is radial; the vertical fracture has larger contact area to the well bore than that of the horizontal fracture, resulting in lower flow resistance in the vertical fracture than that of the horizontal fracture.

CONCLUSIONS

1) Longer and wider fracture can give larger steam production. Thus, it is desirable to enlarge its size by the hydraulic fracturing, to increase well productivity at the operating condition.

2) There is the best combination of fracture length and the fracture width to maximize the well productivity at the operating condition for the same fracture volume. Thus, the balance of the fracture length and fracture width is important in creating fractures by the hydraulic fracturing.

3) The method described in this paper enables us to quantitatively predict the effects of the hydraulic fracturing and evaluate the best combination of the fracture geometry, for planning the best hydraulic fracturing job.

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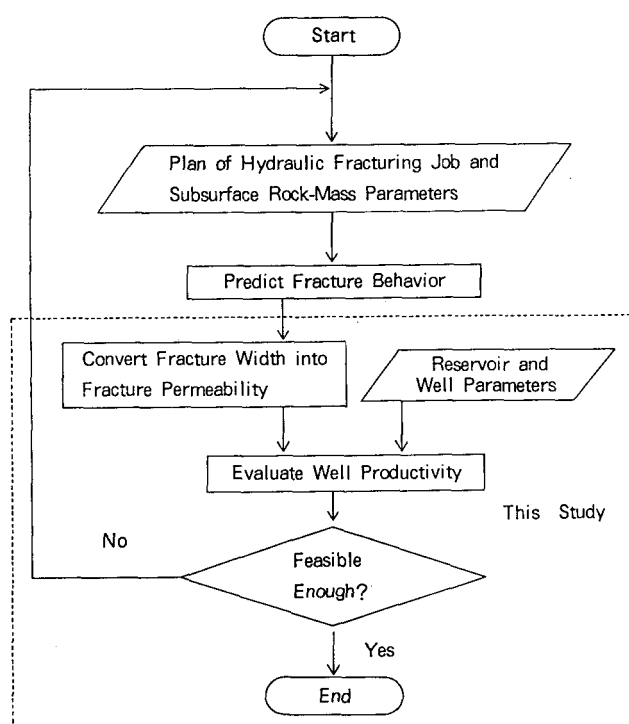


Fig.1 A Flow Chart to Predict and Evaluate Effects of Hydraulic Fracturing Jobs. Items in a Dotted Box are Treated in this Study.

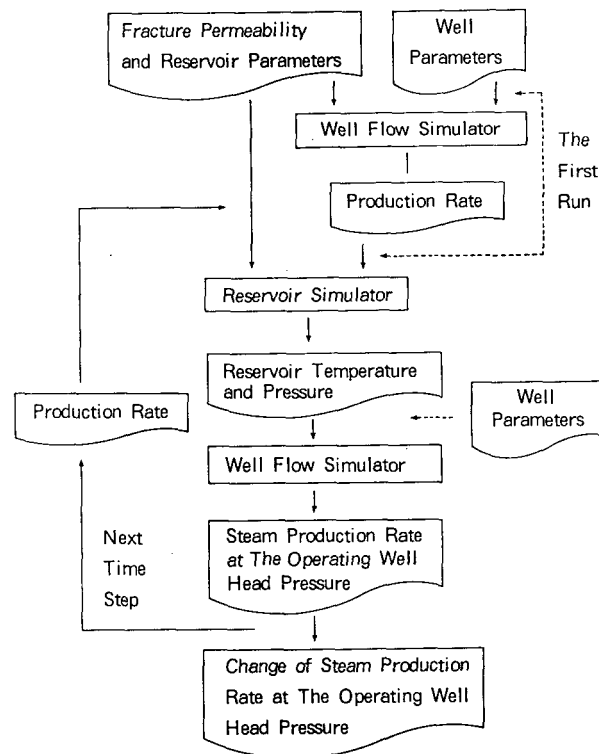


Fig.2 A Flow Chart to Evaluate Well Productivity.

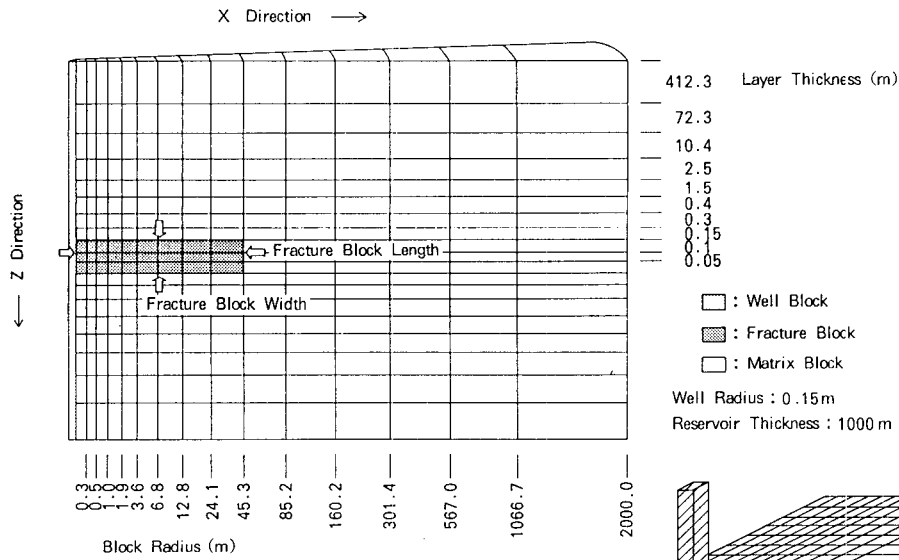


Fig. 3 Grid Geometry of the Horizontal Fracture Model.

Table 1 Simulation Parameters of Horizontal Fracture Model (Fig. 3), Vertical Fracture Model (Fig. 4), and Well Flow Model.

* : Boundary Conditions of One Side of X and Y Direction of the Vertical Fracture Model are Closed.

	Parameter (Symbol)	Value
Horizontal and Vertical Fracture Model	Center Depth of Fracture Layer	2000 m
	Reservoir Pressure at 2000m	20 MPa
	Other Depths	Hydrostatic Pressure
	Reservoir Temperature	230 °C
	Boundary Condition	Open on All Direction (Constant Temp./Press.)
	Porosity	
	Fracture Block	0.8
	Matrix Block	0.1
	Well Block	0.999
	Rock Heat Capacity	2MJ/m ³ ·K
Rock Thermal Conductivity	2W/m·K	
Permeability	Fracture Block	100 × 10 ⁻¹² m ²
	Matrix Block	25 × 10 ⁻¹⁵ m ²
	Well Block	1000 × 10 ⁻¹² m ²
Horizontal Fracture Model	Fracture Block Length (L f)	45.3, 85.2, 160.2 301.4, 567.0 m
	Fracture Block Width (Wf)	0.05, 0.25, 0.55 m
Vertical Fracture Model	Fracture Block Length (L f)	50, 150, 450 m
	Fracture Block Height (H f)	20, 40 m
	Fracture Block Width	0.3 m
Well Flow Model	Well Head Pressure	0.65 MPa
	Depth of Feed Point	2000 m
	Diameter of Well	0.30 m

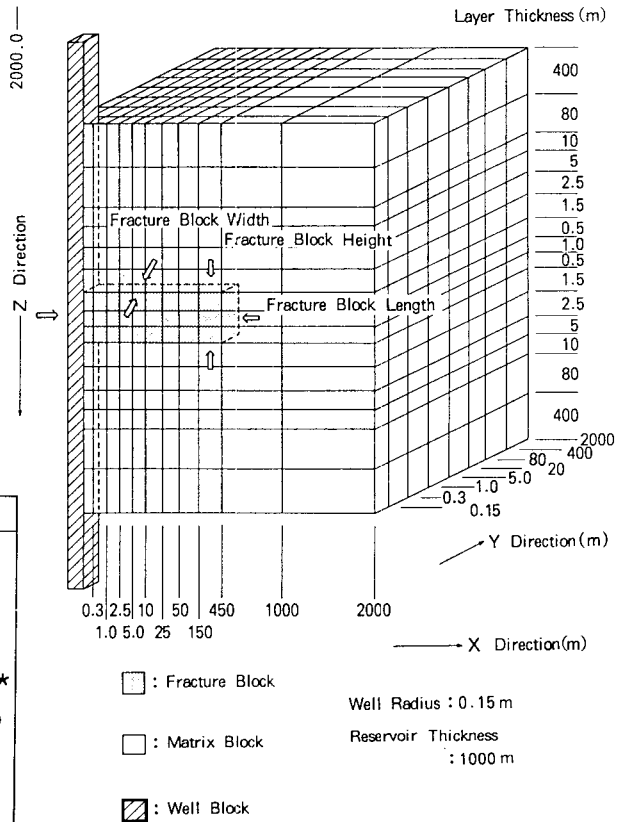


Fig. 4 Grid Geometry of the Vertical Fracture Model.

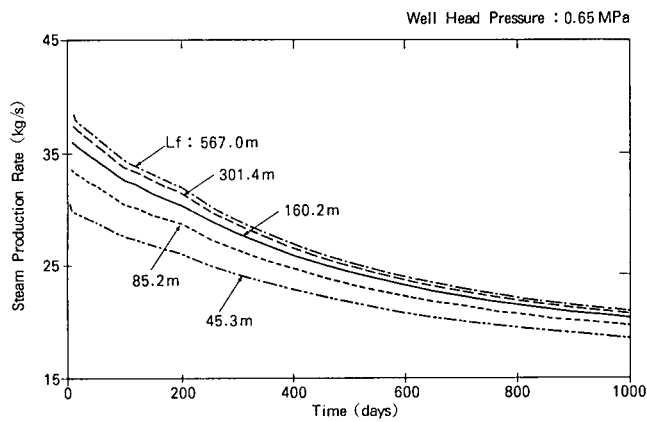


Fig. 5 Change of Steam Production Rate at Constant Well Head Pressure of 0.65MPa (Horizontal Fracture Model, Wf=0.25m).

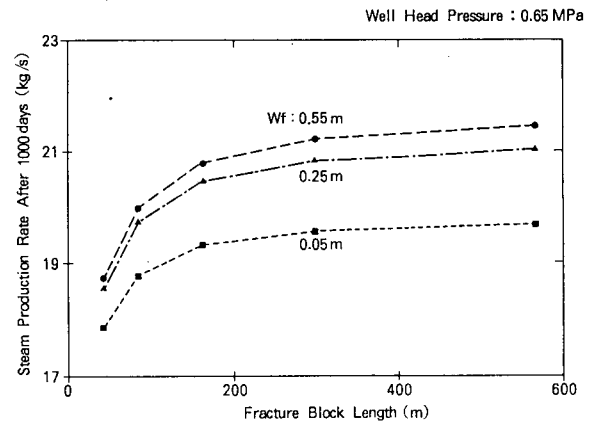


Fig. 6 Differences in Steam Production With Different Fracture Length and Fracture Block Width (Horizontal Fracture Model).

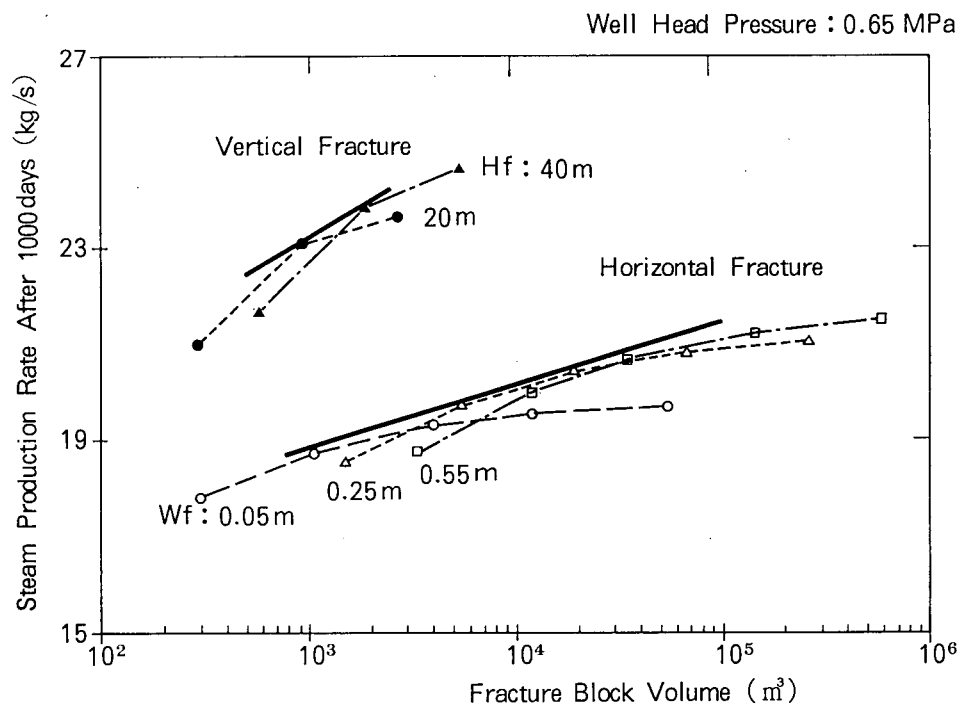


Fig. 7 Steam Productivity of Various Fracture Block Volume of Both the Horizontal Fracture Model and Vertical Fracture Model.