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FUTURE TARGET FOR GEOTHERMAL DEVELOPMENT - FRACTAL FRACTURE MECHANICS AND ITS APPLICATION TO CONCEPTUAL HDR RESERVOIR DESIGN -

Hideaki Takahashi, Kimio Watanabe and Toshiyuki Hashida

Research Institute for Fracture Technology, Faculty of Engineering
Tohoku University, Sendai 980, JAPAN

ABSTRACT

A concept of "Fractal Fracture Mechanics" for HDR (Hot Dry Rock) geothermal reservoir design has been developed as an extension of conventional rock fracture mechanics. It is suggested that this concept is successfully applicable to characterize and model subsurface fracture network in HDR geothermal reservoir.

Furthermore, this modeling procedure makes it possible to evaluate the thermal energy output from the fractal HDR reservoir and its life performance, and to understand the fractal multiple cracking behavior during the hydraulic fracturing.

INTRODUCTION

Since a half century design concept and procedure of pressure vessel and piping system like boiler or nuclear and chemical reactor for energy conversion engineering has been developed as an accumulated and integrated technology system, where there have existed a lot of inventions and improvement in the fields of important basic research area, for example, combustion technology, heat transfer, and material science and engineering.

Nowadays, in fact, the standard design procedure for a power plant boiler of 500 MW has been established as ASME Boiler and Pressure Vessel Design Code. As illustrated in Fig. 1 (a), when the design specification of a power plant is determined, then the conceptual design and engineering details such as type of boiler, area of heat exchanging surface and etc., can be selected, and consequently design engineers can estimate a cost and time schedule for the whole construction.

In geothermal engineering, on the other hand, there has not been established a reasonable basic design procedure for the thermal output from the earth's crust. In another word, there is no standard design procedure for "Geothermal Underground Boiler". Until now, the thermal output and life time of a geothermal power plant is determined only from well logging data obtained for the reservoir concerned. As shown already in Fig. 1 (b), the most important key technologies to establish "Geothermal Boiler Technology" is a design procedure of heat exchange surface in the underground and its life performance estimation. The majority of currently operating geothermal power plants in the world heavily rely on natural geothermal fluid stored in the existing subsurface fracture network.

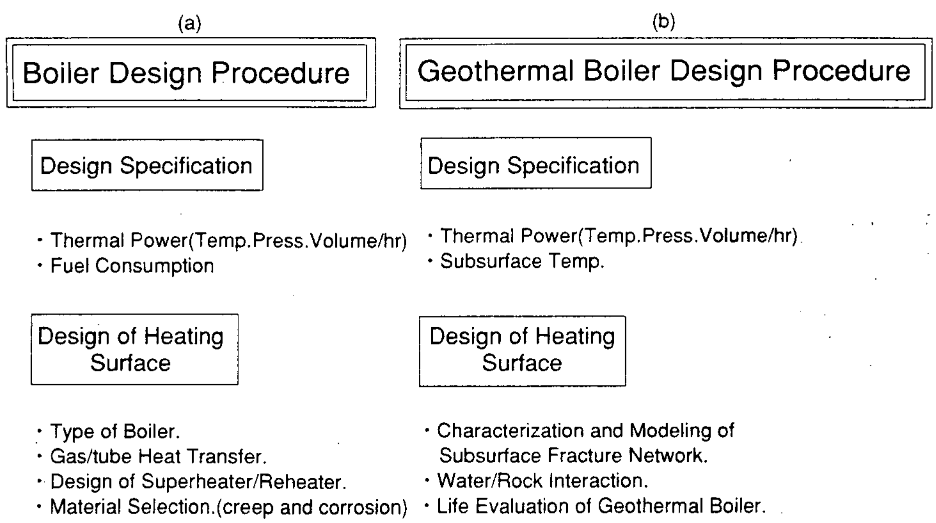

Fig. 1 Comparison of design procedures for conventional boiler and geothermal subsurface boiler.

Therefore thermal output is limited because of the locality, and the potential thermal energy from the surrounding areas is typically not fully utilized and remains unexplored. Here, the basic idea of HDR (Hot Dry Rock) can be applied to extract those potential thermal energy of surrounding areas in the conventional geothermal field, where a name of "HWR (Hot Wet Rock)" was proposed and this HWR system refers to the combined natural and artificial crack network (Takahashi and Hashida, 1992). The research target is directed towards enhancing the geothermal power of existing reservoir. This paper describes a future R&D and target for HDR or combined HDR-HWR geothermal reservoir engineering in next decay, where a contribution of "Fractal Fracture Mechanics" to the geothermal reservoir design is demonstrated and the basic research items to be solved are also discussed.

NEED OF QUANTITATIVE CHARACTERIZATION OF SUBSURFACE FRACTURE NETWORK FOR GEOTHERMAL RESERVOIR

Since 20 years HDR geothermal energy extraction technology has been developed as one of the most attractive energy conversion systems. Although several HDR field experiments demonstrated the strong potential for energy production from the crust, no HDR power plant is realized yet, because hot water circulation systems are still not fully understood and consequently HDR reservoir could not be designed in the engineering base.

Hence, the key technologies for the future HDR development are summarized as follows :

(1) Characterization of fracture networks in a subsurface and their modeling for the HDR reservoir design.
(2) Evaluation of water permeation through the fracture networks and design of the circulation systems.
(3) Evaluation of heat and mass transfer and their change during HDR life time.
(4) Mechanical response of fractal fracture network during hydraulic fracturing stimulation and service operation.

Among those key technologies mentioned above, it is first of all important that three-dimensional fracture network systems in the crust are fully understood and modeled reasonably based on the geological background.

Geometrical similarity of the fracture patterns has been reported often in the literature, where various fractures from the microscopic grain-size fracture (~1 mm) to macroscopic fault-size fracture (~1 km) were described and characterized. Recently strong attention has been paid on "fractal geometry" to explain and characterize those fracture patterns.

Although as described previously, no HDR power plant is available, there are many conventional geothermal power plants in the world. Their thermal outputs per unit power station are limited c/a 30~50 MW, on average, to prevent thermal draw down and keep long life performance.

Figure 2 shows an illustrative sketch of the future research and development target not only for the traditional geothermal energy extraction but also for the HDR reservoir design.

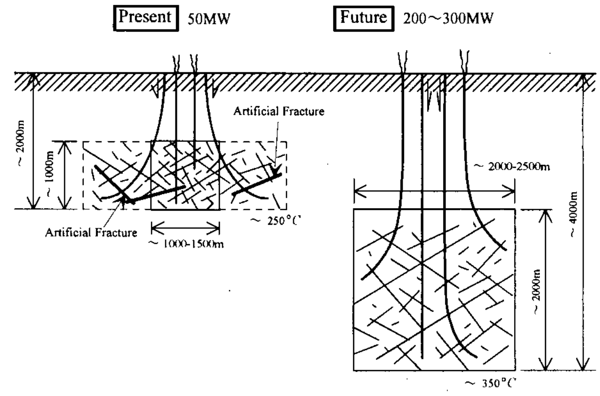

Fig. 2 Future target for geothermal energy extraction from HDR/HWR reservoir making use of subsurface fracture networks.

It is understood that thermal output of 30~50 MW seems to be the optimal energy output from a 1 km cube of rock of ~250°C temperature. Next-generation HDR energy extraction from deep crust provides us the potential for large capacity power plants (~300 MW). An image of our future HDR reservoir is illustrated also in Fig. 2, where the depth of well attains 4~5 km, and rock temperature ~350°C. The size of the HDR reservoir is a 2 km cube. After we can understand the fracture networks, water circulation and thermal output within a 1 km cube quantitatively and it can be modeled by use of simple methodology, a scale-up to 2 km cube HDR reservoir is easily achieved. In Fig. 2 there are illustrated two-dimensional fracture network systems by which the water circulation from inlet well to production well and energy extraction could be made.

FRACTAL FRACTURE NETWORK RESERVOIR MODEL

Recently, Watanabe and Takahashi (1995) proposed a two-dimensional modeling technique for subsurface fracture networks on the basis of "fractal geometry" as a new procedure for modeling geothermal energy extraction system. This procedure makes it possible to characterize geothermal reserves by parameters measured from field data such as core sampling. This two-dimensional model can be easily extended to three-dimensional model as described as following.

There is essentially no information available concerning the three-dimensional shape of subsurface fractures. In this paper, therefore, we assume the subsurface fractures to be penny-shaped as in the analysis by Koldith (1993) and Willis-Richards et al. (1995), and the diameter distribution to be fractal in which the relation between fracture length, r and the number of fractures, N whose lengths are equal to or larger than r can be expressed by the following fractal equation :

$$N = C \cdot r^{-D} \qquad (1)$$

where C is a constant and D is a fractal dimension.

Figure 3 shows the concept of the three-dimensional fracture network model, and a schematic of the fracture network water circulation system. The network is generated by distributing a fractal size distribution of penny-shaped fractures with random orientations to random positions in the cube. In order to simplify and generalize the discussion, the area and the fractures are normalized by the size of cubic.

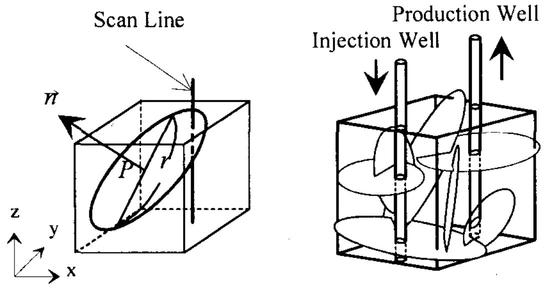

Fig. 3 General concept of the individual fracture generation for the three-dimensional fracture network model and a schematic of the fracture network water circulation model.

In this normalized model, the total number of fractures is expressed by the symbol n, and the ith (i=1,2,...,n) fracture is characterized by the following three parameters: mid-point of the fracture, p_i; normal to the fracture plane : $\vec{n}_i$; and diameter of the fracture : r_i. Similarly, fracture network patterns are characterized by the following three parameters : the total number of fractures, n; fractal dimension, D; and fracture density parameter, C. In this paper, these parameters are determined as follows.

Mid-point of the fracture, p_i. It is assumed that the fractures do not interact to form clusters, so the x, y and z co-ordinates of the point p_i are determined by using random numbers lying between 0 and 1.

Normal to the fracture plane, $\vec{n}_i$. The distribution of $\vec{n}_i$ often appears to be random, but observations of fractures in borehole cores and in the field commonly show that fracture sets have preferred orientations. Therefore, if it is possible to obtain the preferred orientations, $\vec{n}_i$ must be determined to have the same tendency as that of the field data. In this study, however, only a random distribution of normal to the fracture plane is used.

Diameter of the fracture, r_i. Since the diameter distribution of the fractures is governed by fractal geometry, the distribution of values of r_i must satisfy equation (1). In order to satisfy equation (1), r_i is determined by the following formula :

$$r_i = (C / i)^{1/D} \qquad (2)$$

Total number of fractures, n. Theoretically, if we were to consider very small fractures whose lengths approach zero, then n would approach infinity. However, very small fractures cannot be observed, and the minimum fracture size which can be observed is dependent upon the resolution of the measuring instrument. In this paper, r_{min} is defined as the smallest length of fracture which must be considered for the analysis. Although we do not discuss the details here, pre-calculation has shown that fractures with normalized lengths smaller than 0.1 exert only a very small influence on the permeability. So, we have set the value of r_{min} as 0.1, and the smallest value of i which satisfies $r_i > r_{min}$ is accepted as the value of n.

Fractal dimension, D. Although some fault systems have been investigated and their fractal dimensions calculated by the box-counting method, the fractal dimensions required for equation (1) are not available. As described above, Main et al. (1990) have reported the relationship between the fracture length and the number of fractures at four different scale fault systems and shown that the fractal dimensions of all fault systems are almost equal to 1. Because geothermal energy extraction systems often make use of natural fault systems in the reservoir for water flow paths, it is reasonable to adapt the same value obtained by Main et al. (1990) to geothermal reservoir models. Theoretically a three-dimensional fractal dimension must be 2.0 to get a fractal distribution of fracture lengths with D=1.0 on the section areas of the three-dimensional model proposed here. So, the fractal dimension of the three-dimensional fracture network model is assumed to be 2.0 in this present work.

Fracture density parameter, C. Once the total number of fractures and their fractal dimension are determined, then the fracture network models can be described simply by parameter C alone. In this study, parameter C is used as the model comparison parameter. For actual geothermal sites, it is also possible to estimate the value of parameter C based on field data. It is relatively easy to measure the number of fractures per unit length that are observed on core material that samples a borehole interval of interest. If we then consider a borehole as a scan-line of a subsurface fracture network as shown in Figure 3, it is possible to predict the number of fractures observed per unit length of core m by the following equation :

$$m = \overline{\sin\theta_i} \cdot \left\{ \int_{r_{min}}^{1} \pi \cdot \left(\frac{r}{2}\right)^2 \cdot \left(-\frac{dN(r)}{dr}\right) dr + C \right\} \qquad (3)$$

where $\overline{\sin\theta_i}$ is the average sin of all the angles of fractures from horizontal, θ_i. From equation (3), the parameter C

can be calculated according to :

$$C = \frac{4m}{\sin\theta_i \cdot \left\{9\pi \cdot \left(1 - r_{\min}^{0.2}\right) + 1\right\}} \qquad (4)$$

CONCEPTUAL HDR RESERVOIR DESIGN PROCEDURE BASED ON FRACTAL FRACTURE MECHANICS

Figure 4 illustrates a basic concept of "Fractal Fracture Mechanics", where three essential parameters, crack distribution, crustal stress data and fracture toughness of rocks are interrelated each other as a fracture mechanics parameter.

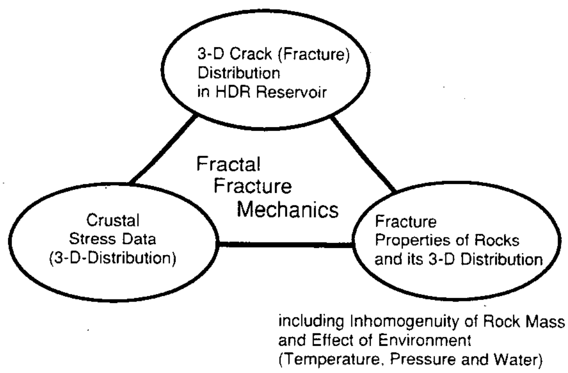

Fig. 4 Concept of fractal fracture mechanics with three essential geophysical parameter.

Because, in the previous section described above, there is no quantitative information of three-dimensional information of subsurface fracture network, a simple three dimensional model for HDR reservoir was proposed by use of circular shaped fracture (Watanabe and Takahashi, 1993, 1995). Figure 5 is an example of R&D program of a conceptual HDR reservoir design procedure based on "Fractal Fracture Mechanics". This design flow chart presents a fundamental step of the Fractal Fracture Mechanics applied to HDR reservoir modeling by use of core sample information. Until now this design procedure is not yet established as the whole system technology. However, the conventional fracture mechanics can be used as a fundamental tool and be modified for subsurface application. In the conventional fracture mechanics, a single crack problem is a typical one, while there are naturally created multiple cracks (fractures) within HDR reservoir. Therefore it is strongly needed to develop a standard procedure to characterize three-dimensional crack system in the reservoir from borehole data such as core sample or BHTV. When the fracture network is known, then fluid flow and heat transfer analysis can be made even for the complicated fracture system as mentioned later.

EVALUATION OF THERMAL OUTPUT FROM THREE-DIMENSIONAL FRACTAL HDR RESERVOIR AND ITS LIFE PERFORMANCE

Single Fracture and Permeable Zone Models

In the first instance, it is important to estimate geothermal energy extraction performances from the single fracture and permeable zone models since these will provide respectively the lower and upper bounds of the reservoir performance due to the total area of heat exchange surface.

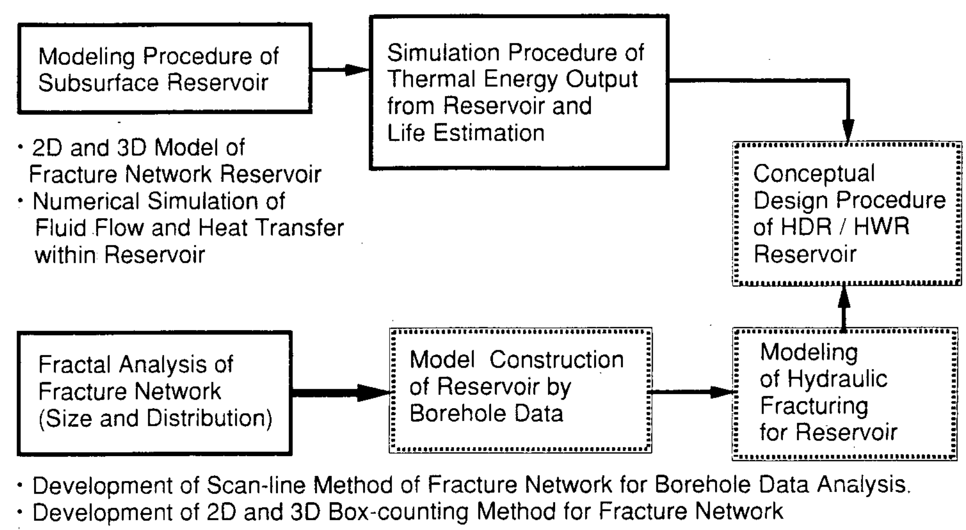

Fig. 5 An example of R&D program for establishing the conceptual design procedure of HDR reservoir based on fractal fracture mechanics.

Figure 6 illustrates the three-dimensional single fracture and permeable zone models used in this study. In the single fracture model, water flow occurs only through one fracture which connects the injection well and the production well as shown in Fig. 6. The permeable zone model is considered as an equivalent of the fracture network model in which fractures fill the volume uniformly. These two models are the ideal examples of the fracture network model.

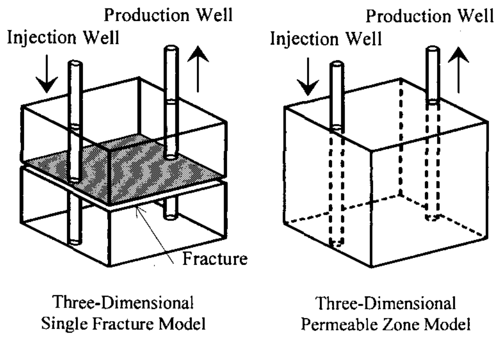

Fig. 6 Three-dimensional single fracture and permeable zone models.

Water Flow Model

Assuming that the density of water is constant at every point and temperature within the model reservoir volume, the water flow through the permeable volume can be expressed by :

$$k_x \cdot \frac{d^2P}{dx^2} + k_y \cdot \frac{d^2P}{dy^2} + k_z \cdot \frac{d^2P}{dz^2} = 0 \qquad (5)$$

where P is the water pressure, and k_x, k_y and k_z represent the permeability in the x, y and z directions. For numerical calculations, the volume of interest is divided into a mesh of small elements. In this paper, the local permeability is given between elements in the mesh where fractures intersect element interfaces as shown in Fig. 7.

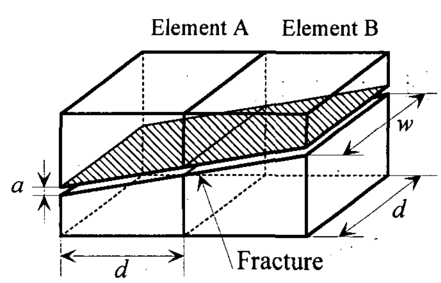

Fig. 7 Definition of local permeability between elements where a fracture intersects the boundary.

Although the apertures of natural fractures are not spatially uniform and an "effective" aperture should therefore be calculated, we have assumed that water flow can be approximated by that in a parallel-sided fracture with some constant effective aperture. According to the cubic flow law, the quantity of water flowing between elements, q_i, can be expressed by :

$$q_i = \alpha \cdot w \cdot a^3 \cdot \Delta P / d \qquad (i = x, y, x) \qquad (6)$$

where a and w express the aperture and the width of fracture intersecting the element interface, and ΔP is the difference in fluid pressure between the two elements. d is the element size and α is a constant.

In this model, the local permeability between elements is defined as :

$$k_i = u_i \Big/ \left(\frac{\Delta P}{d}\right) = \left(\frac{q_i}{d^2}\right) \Big/ \left(\frac{\Delta P}{d}\right) = \alpha \cdot \frac{w \cdot a^3}{d^2} \qquad (7)$$

where u_i is the water velocity, and i symbolizes the directions x, y and z. The effective aperture of fractures is assumed to be proportional to the fracture lengths according to :

$$a = \beta \cdot r \qquad (8)$$

therefore :

$$k_i = \gamma \cdot w \cdot r^3 \qquad (\gamma = \alpha \cdot \beta^3 / d^2) \qquad (9)$$

where β *and* γ are constants.

In this study, the local permeability is alsó normalized to the permeability of the whole mesh by the following equation :

$$k_i{*} = \frac{\gamma \cdot w \cdot r^3}{\gamma \cdot d \cdot L^3} = \frac{w \cdot r^3}{d \cdot L^3} \qquad (10)$$

Thermal Transfer Model

The model used to calculate the thermal transfer is shown in Fig. 8. In Fig. 8, the dotted line indicates the adiabatic thermal boundary for the calculation of thermal transfer, and LE represents the distance to the thermal boundary. LE is determined by a theoretical calculation of the one-dimensional heat transfer rate to be the minimum distance for approximately zero temperature change over the time scale of interest.

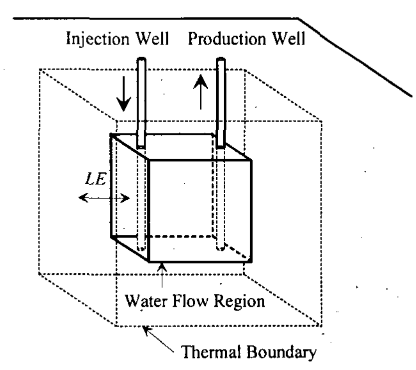

Fig. 8 Thermal transfer model. The solid lines express the water flow region where no water flows occur. The dotted lines express the adiabatic thermal boundary.

The following equation is used for the calculation of thermal transfer :

$$C_R \cdot \rho_R \cdot \frac{\partial T}{\partial t} + C_W \cdot \rho_W \cdot \left(u_x \cdot \frac{\partial T}{\partial x} + u_y \cdot \frac{\partial T}{\partial y} + u_z \cdot \frac{\partial T}{\partial z} \right) = \lambda \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (11)$$

where T is the temperature of the rock (equal to the temperature of the water in this calculation) and t is time. λ is the thermal conductivity of the rock. C_R and C_W are respectively the specific heats of the rock and the water, ρ_R and ρ_W are respectively the densities of the rock and the water, and u_x, u_y and u_z are the water velocities in each direction. Normalized value of temperature, T^*, time, t^*, water velocity, u_x^*, u_y^*, u_z^* and quantity of circulating water, Q^* are defined as follows :

$$T^* = \frac{T - T_0}{T_\infty - T_0} \quad (12), \qquad t^* = \frac{\lambda \cdot t}{C_R \cdot \rho_R \cdot L^2} \quad (13)$$

$$u_i^* = \frac{L \cdot C_W \cdot \rho_W \cdot u_i}{\lambda} \quad (14), \qquad Q^* = \frac{C_W \cdot \rho_W \cdot Q}{L \cdot \lambda} \quad (15)$$

where T_∞ and T_0 define the initial temperatures of the rock mass and the water in the injection well, respectively. Q is the quantity of circulating water.

Changes in Thermal Output with Time

The thermal energy output profile is the most important parameter for performance estimation. Hence, We define the normalized thermal energy output E^* as :

$$E^* = Q^* \cdot T^* \quad (16)$$

Figure 9 shows the changes in E^* with time for each reservoir model. The thermal energy change for a single water quantity of Q^*=100 has been used to compare the performance of each model. Three fracture network models with different fracture densities (C=2.0, C=4.0, C=6.0) have been used. Because our fracture network model is generated using random numbers, each profile of thermal energy output is obtained from the average value of 20 trials with different random seeds.

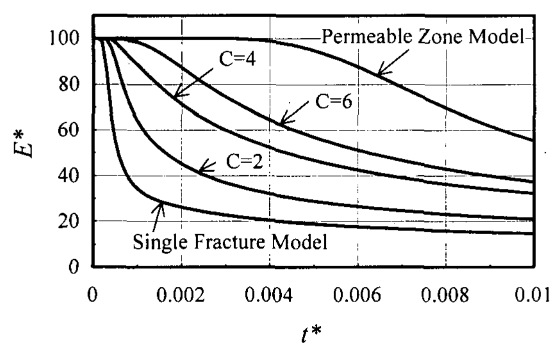

Fig. 9 Changes in the thermal energy outputs for the single fracture and permeable zone models, and the variants of the fracture network model.

OPTIMUM DESIGN AND POTENTIAL ANALYSIS

Design Optimization of Energy Extraction

For economically effective energy extraction, the optimum design of HDR systems must be discussed. Although there are many factors to be considered for the optimum system design, here, we use only the normalized optimum quantity of circulating water Q^* as the optimization parameter. Because the temperature of a geothermal reservoir decreases with heat energy extraction, it is necessary to define the normalized reservoir life, t_{life}^*. In this study, the normalized temperature threshold of production water, T_{th}^* is used to determine t_{life}^* as shown in Fig. 10.

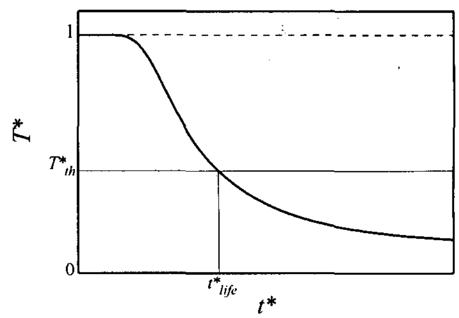

Fig. 10 Definition of the normalized reservoir life.

T_{th}^* is the lowest temperature at which economical energy production is possible. As we saw in the previous section, the normalized temperature of production water decreases as fracture density, quantity of circulating water and time all increase. The reservoir life, t_{life}^* is defined as the point where the normalized temperature of production water reaches T_{th}^*, as also shown in Fig. 10. Once T_{th}^* is fixed, and the fracture density is obtained, t_{life}^* can be predicted as a function of Q^* as shown in Fig. 11.

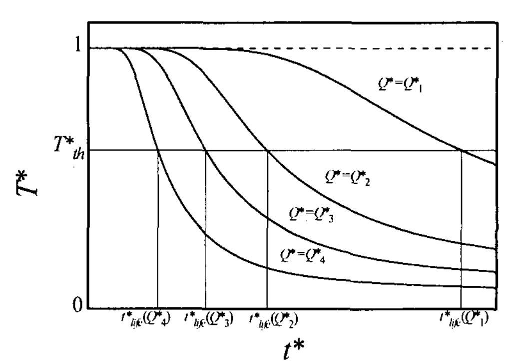

Fig. 11 The relationship between the reservoir life and the quantity of circulation water.

For optimized systems, t_{life}^* should be equal to the design life. It is possible to set the value of T_{th}^* to be equivalent to the design life by controlling Q^*. In this study, the optimum design requires us to find the value of Q^* which give the same value of t_{life}* as the design life, and this value of Q* for each system is defined as the normalized optimum quantity of circulating water, Q^*_{opt}. Fig. 12 shows the relationship between Q^*_{opt} and t_{life}* for T_{th}*=0.5, and it is found that the relationship is linear in log-log space.

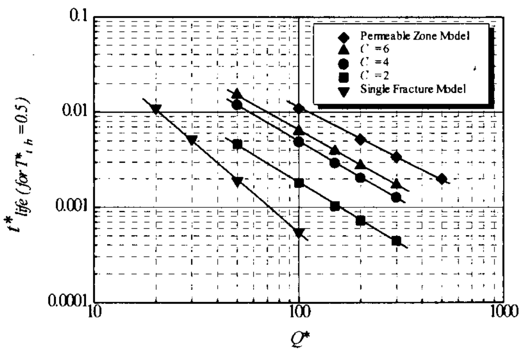

Fig. 12 The normalized optimum design curve. Each line shows the optimum quantity of circulating water for the reservoir life (design life).

Potential of Energy Extraction from HDR

To estimate the potential of HDR systems, a numerical analysis of energy extraction from optimized HDR systems, i. e., those with an optimized quantity of circulation water, has been performed. Fig. 13 shows the relationship between reservoir size and maximum energy output transformed from normalized values using following conditions and the thermal properties.

Initial temperature of rock mass : 200°C
Temperature of injection water : 100°C
T_{th}* : 150°C, t_{life}* : 20 years
$\lambda = 2.40\, W/m\cdot K$
$C_R = 1.20\times10^3\, J/K\cdot kg$, $\rho_R = 2.26\times10^3\, kg/m^3$
$C_W = 4.48\times10^3\, J/K\cdot kg$, $\rho_W = 8.68\times10^2\, kg/m^3$

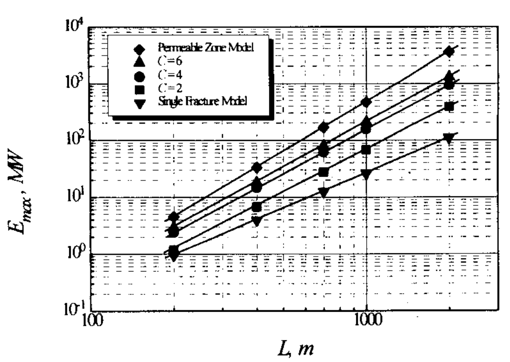

Fig. 13 The maximum thermal energy output from HDR with the optimum quantity of circulation water.

From Fig. 13 it can be predicted that a 2km x 2km x 2km HDR reservoir which has a relatively high fracture density (C=4.0) can produce more than 300 MW under optimized operational conditions. This shows the great potential of HDR geothermal energy extraction as a new energy production technique.

FRACTAL FRACTURE MECHANICS MODEL OF HYDRAULIC FRACTURING

In this section, outline of a numerical simulation model is presented which was used to study the crack pattern induced by hydraulic fracturing in a fractured rock mass in two dimensions, and some preliminary results are given.

The model employs the Fluid Rock Interaction Program (FRIP)(Cundall, 1983; Markland, 1992), but a beam model is built into the simulation code so that the growth behavior of newly created crack by hydraulic fracturing can be simulated in addition to the stimulation of pre-existing cracks in the fractured rock mass. The model consists of a regular grid of elastic blocks separated by weak planes. An elastic beam network is constructed on the grid model such that two neighboring grids are bridged by the elastic beam. The beams are rigidly connected at the center of the grid. The elastic beam represents the cohesive strength of the weak plane in which the fluid flow occurs. The fluid flow in the weak plane is allowed to occur when the tensile stress in the beam reaches the fracture strength of the rock. The elastic modulus and the cross sectional dimensions of the elastic beams are selected to simulate the elastic properties of the rock.

In order to simulate the pre-existing cracks in rock masses, the cohesive strength along the weak plane is set to be zero; namely the elastic beam across the pre-existing cracks is broken before fluid injection is applied. A population of pre-existing cracks varying in size and orientation is generated stochastically. A fractal distribution is assumed for the crack size, and the crack orientation and location is assumed to be random.

Numerical simulations were conducted to examine the effects of the density of the pre-existing cracks and the fractal dimension on the hydraulically induced crack pattern. The initial crack densities used in the simulations were 5, 7.5, 10, 15 and 20 %, and the fractal dimensions for the crack size were 1.0, 1.4 and 1.8. In order to characterize the size of the stimulated reservoir, the number of the stimulated cracks , i.e. the broken beams within the square grid model were counted. The relationship between the number of the stimulated cracks and the initial crack parameters is shown in Fig. 14 along with typical crack patterns obtained by the above procedure on a square grid model 50 x 50 with a free external boundary. The dimensions of the grids are 0.1 m x 0.1 m. The incompressible fluid is injected at the center of the grid model. The thick line indicated in the grid model shows the stimulated reservoir. It appears that the number of the stimulated cracks (total flow area) primarily depends on the initial crack density.

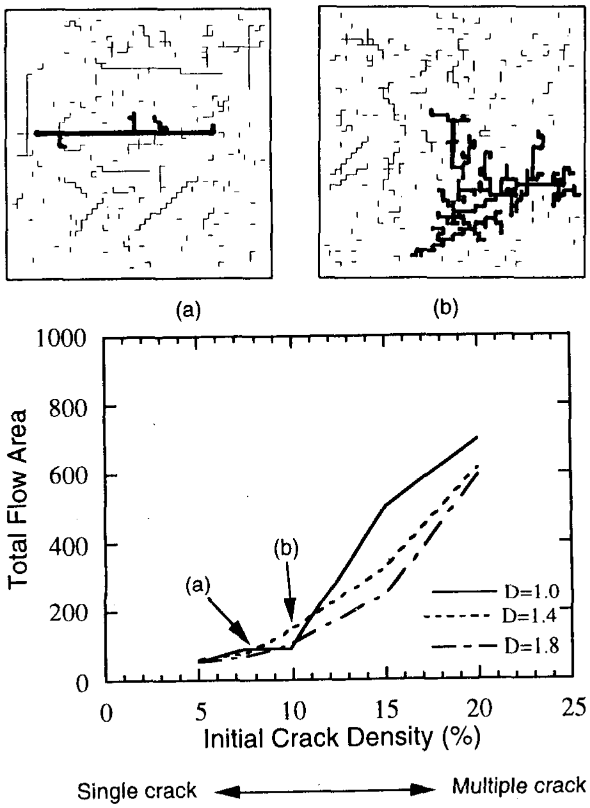

Fig. 14 Transition of the hydraulically induced crack pattern

Furthermore, it is shown that the crack pattern transition from a single crack to the multiple crack type reservoir occurs approximately above the initial crack density of 10 %. Information regarding the initial crack density can be obtained from a borehole survey. Thus, it may be possible to predict the reservoir type using the present hydraulic fracturing model combined with such field data. There has been reported the very similar crack patterns created by hydraulic fracture simulation (Herrmann et al., 1993). More rigorous three-dimensional simulation model which allows for the pressure gradient in the crack and the growth of shear dilation along pre-existing cracks is currently being developed at Tohoku University.

CONCLUDING REMARKS

With special reference to fracture network in the HDR/HWR geothermal reservoir, the concept of "Fractal Fracture Mechanics" was proposed to develop a conceptual design procedure for the geothermal boiler.
In order to establish this concept, the further development of both fundamental methodology and careful accumulation of field examples would facilitate during next 10 years.

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Recently the keyword "Fractal Fracture Mechanics" has been also proposed by Dr P.G. Meredith (UCL, London) and Prof. I. G. Main (Univ. of Edinburgh) in United Kingdom. Authors would like to acknowledge them for JSPS-British Council collaboration research project on "Fractal Fracture Mechanics" (1992-94).

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