Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

NUMERICAL STUDY ON HEAT EXTRACTION FROM SUPERCRITICAL GEOTHERMAL RESERVOIR

Kimio Watanabe[1], Yuichi Niibori[2] and Toshiyuki Hashida[2]

[1]RichStone Ltd., 2-45 Aomi, Koto-ku, Tokyo 135-8073, Japan
[2]Graduate School of Tohoku University, Aramaki Aoba, Aoba-ku, Sendai 980-8579, Japan

Key Words: supercritical, geothermal, heat extraction

ABSTRACT

Recent technology makes it possible to dig a well into the subsurface rocks whose temperatures exceed 400 °C. These geothermal reservoirs are filled with supercritical water. It is known that water properties significantly change near critical point. Especially heat capacity of water increases dramatically. This means that supercritical water can sweep thermal energy from rock more efficiently than non-supercritical water. In this study, the potential of heat extraction from supercritical geothermal reservoirs, as an extension of Hot Dry Rock / Hot Wet Rock technology, is theoretically evaluated. A numerical analysis code for water flow in fractured rock and heat exchange between rock and water considering changes of water properties is developed. Based on the water circulation model of a single fracture with one injection well and one production well, the changes of water flow patterns with time and efficiency of heat extraction are analyzed. Water flow patterns change during heat extraction due to the changes water properties, and efficiency of heat extraction strongly depends on initial temperature of surrounding rock. Finally, on the point of view of heat extraction efficiency, advantages and disadvantages of using supercritical geothermal reservoirs are summarized.

1. INTRODUCTION

As one of new techniques to extract geothermal energy, Hot Dry Rock (HDR) / Hot Wet Rock (HWR) geothermal energy extraction systems have received much attention (e.g. Tester, Brown and Potter, 1989; Takahashi and Hashida, 1992). The basic concept of these systems is to develop a water circulation system through the subsurface fracture network in HDR (without natural water flow system) or HWR (with natural water flow system). Although no commercial plants have yet been constructed, individual technologies such as drilling, measuring, hydraulic stimulation and numerical analysis are improving. Because recent drilling technology makes it possible to dig geothermal wells into supercritical reservoir, this study evaluates possibility and efficiency of heat extraction from supercritical geothermal reservoirs. It is well known that water properties, such as density and specific heat, change dramatically near critical point. For the water flow and heat extraction analysis of HDR/HWR systems whose reservoir temperatures get supercritical, behavior of water properties must be considered. In this study, following two groups of water properties that may affect heat extraction efficiency of HDR/HWR systems are chosen for the evaluation.

(1) Density and Viscosity: These may affect water flow patterns.

(2) Specific enthalpy: This may affect capacity of thermal energy transport.

Their changes with temperature and pressure are summarized including supercritical region. A new simulation code for water flow and heat transfer considering water properties as functions of temperature and pressure is developed. Using the simulation code, heat extraction from supercritical reservoirs compared with non-supercritical reservoirs is evaluated.

2. CHANGES IN WATER PROPERTIES

Water properties including supercritical region are well investigated and established (JSME Steam Table in SI, 1980), and the equations to calculate the each water property are proposed. However these equations are too complicated in terms of calculation time to adopt simulation code for heat extraction analysis for HDR/HWR systems. In this study, matrixes of each property (property tables) within certain temperature and pressure are constructed. Values of water properties at every element in the model are picked out from these tables at each time step. Density and viscosity of water are calculated in this manner. Figure 1 and Figure 2 show density and viscosity of water within temperature region from 0 °C to 800 °C, and pressure region from 30 MPa to 100 MPa.

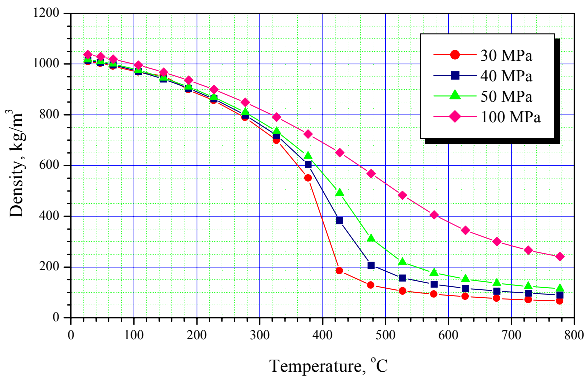

Figure 1. Density of water with temperature increase under pressure condition 30, 40, 50 and 100 MPa.

Density of water slowly decreases with temperature increase until temperature reaches critical point. Above critical point and under relatively low-pressure condition in Figure 1, density of water dramatically decreases and becomes stable with temperature increase. However, under high-pressure condition, the density of water changes slowly. On the other hand, viscosity of water decreases in early stage of temperature increase, and receives small influence from pressure. Figure 2 suggests that it is insignificant for viscosity of water whether water is supercritical or not.

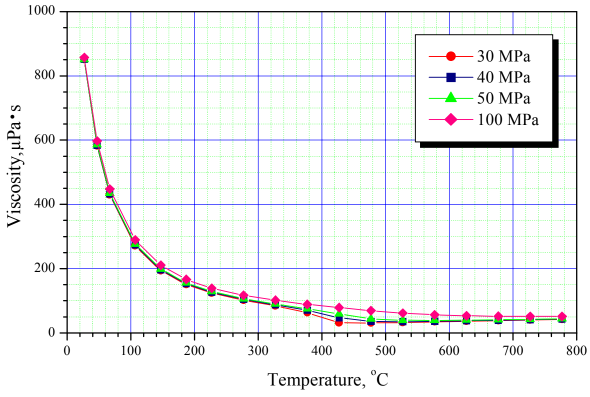

Figure 2. Viscosity of water with temperature increase under pressure condition 30, 40, 50 and 100 MPa.

For the estimation of heat extraction, thermal properties of water that related to heat transfer ability, are also important as well as flow properties. Thermal energy of water per unit weight can be expressed by specific enthalpy. In this study specific enthalpy is used to express water condition at each element and each time, as well as temperature. Specific enthalpy is also used as a function of temperature and pressure in the numerical analysis. Figure 3 shows the changes of specific enthalpy with temperature increase.

Under relatively low-pressure conditions in Figure 3, the rate of increase of specific enthalpy becomes high near critical point. However, under high-pressure condition, it is almost constant. Because the differential value of Figure 3 expresses thermal capacity, water at the temperature near critical point under low-pressure condition has high capacity to contain thermal energy. In other words, if non-supercritical injection water becomes supercritical production water, large thermal energy is extracted from rock mass, even if the difference of temperature is small.

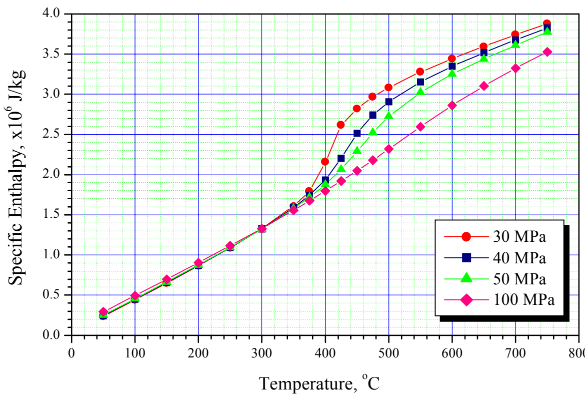

Figure 3. Specific enthalpy of water with temperature increase under pressure condition 30, 40, 50 and 100 MPa.

3. GRID STRUCTURE OF THE MODEL

Fracture systems in the crust are complicated. Several types of network models for the complicated fracture distribution have been proposed (e.g. Watanabe and Takahashi, 1995). In this study, a three-dimensional reservoir model with a single fracture, which is traditionally used for the heat extraction analysis of HDR systems (e.g. Gringarten, Witherspoon and Ohnishi, 1975), is applied. The grid image and fracture location of the model are shown in Figure 4. Water flows only within an idealized "parallel-sided plane" fracture.

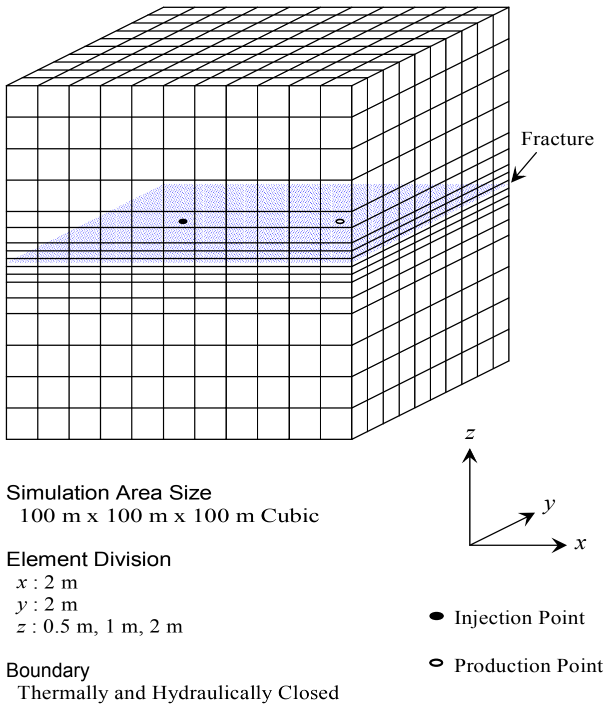

Figure 4. Schematic figure of simulation grid structure and the location of fracture, injection well and production well.

The size of the model is set 100 m cubic. The area is firstly divided into 2 m cubic elements. Then, elements near the fracture are divided again vertically to 1 m and 0.5 m height elements. No heat and water flow occurs at all (top, bottom and side) boundaries, that causes pessimistic estimation of heat extraction and 100 % water recovery. The injection and production wells are located at the distance of 25 m from side boundary in x direction as illustrated in Figure 4. So, the distance between wells is 50 m.

It is assumed that water flow can be approximated by that in a parallel-sided fracture with some constant effective aperture, although the apertures of natural fractures are not spatially uniform. According to the cubic law, the quantity of water between elements, Q (kg/s), can be expressed by the following equation.

$$Q = D \cdot \rho(T,P) \cdot \frac{a^3}{\mu(T,P)} \cdot \frac{\Delta P}{D} \qquad (1)$$

Where ρ (kg/m^3) and μ (Pa·s) express density and viscosity of water that are functions of temperature, T, (°C) and pressure, P (Pa). a (m) is the fracture aperture, and D (m) is the element size. Fracture aperture may also be affected by temperature and pressure of water. However, the relation between fracture aperture and water condition in supercritical reservoirs is not well established. Since this study is a first step for the analysis of supercritical geothermal reservoirs, fracture aperture of the model is fixed.

4. FLOW MODELS AND INITIAL CONDITION

In order to estimate the effect of water properties on water flow, two models, Model-1 and Model-2 are introduced for the analysis. Density and viscosity of water are constants in Model-1, but are functions of temperature and pressure in Model-2. However, specific enthalpy is the function of temperature and pressure for both models as described in Figure 5.

4.1 Model-1

Although density and viscosity of water can be expressed as functions described above, in this model, both properties are treated as constants. This is due to the uncertainty of fracture aperture response against water temperature and pressure, and is to estimate the influence of only specific enthalpy change. Therefore, the quantity of water expressed by equation (1) can be transformed as follows.

$$Q = K_1 \cdot \Delta P \quad (2)$$

Where K_1 is a constant, which is calculated based on water properties at 300 °C, 30 MPa. The fracture aperture of the model is fixed at 0.1 mm.

4.2 Model-2

Density and viscosity of water are calculated at each element and time-step as functions of temperature and pressure. The fracture aperture is 0.1 mm same as the model-1. Equation (1) is simplified to following equation.

$$Q = K_2 \cdot \frac{\rho(T,P)}{\mu(T,P)} \cdot \Delta P \quad (3)$$

Where K_2 is a constant.
For a given pressure difference, quantity of water between elements is ruled by the value of density/viscosity in equation (3). The variation of the density/viscosity with temperature and pressure is shown in Figure 5.

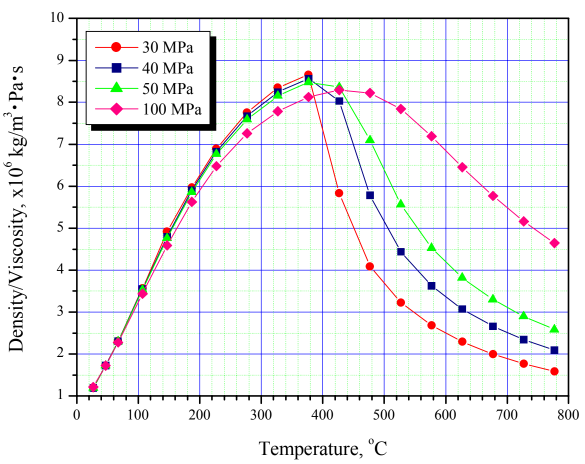

Figure 5. Values of the density/viscosity with temperature increase under pressure condition 30, 40, 50 and 100 MPa.

Figure 5 shows that the quantity of water becomes maximum value near critical point, when density and viscosity of water are treated as functions of temperature and pressure (Model-2). This means that fracture area whose temperature near critical point behaves as a main flow path. This area may move during heat extraction.

4.3 Initial Temperature

To compare the heat extraction efficiency of non-supercritical and supercritical geothermal reservoirs, two initial conditions are adopted as follows.

(a) Low Initial Temperature (Non-supercritical reservoir).
Initial Rock Temperature (T_{R0}): 300 °C
Injection Water Temperature (T_{INJ}): 100 °C

(b) High Initial Temperature (Supercritical reservoir).
Initial Rock Temperature (T_{R0}): 500 °C
Injection Water Temperature (T_{INJ}): 300 °C

The temperature difference between initial rock and injection water is same for both cases, in order to give same values of maximum thermal energy that can be extracted theoretically. Since no heat flow occurs at the boundary, the maximum thermal energy is equal to the energy that 100 m cubic rock mass produces when the temperature decreases 200 °C. Assuming that rock properties are constant with temperature change, the energy can be calculated as follows.

Specific heat × Density × Volume × (T_{R0}-T_{INJ}) =

1.2×10^3 (J/kg·K) × 2.7×10^3 (kg/m^3) ×
1.0×10^6 (m^3) × 200 (°C) = $\underline{6.48\times10^{14}}$ (J)

Following four combinations of the models and initial temperatures are used for the analysis.

Ex-1L: Model-1, Low Initial Temperature
Ex-1H: Model-1, High Initial Temperature (supercritical)
Ex-2L: Model-2, Low Initial Temperature
Ex-2H: Model-2, High Initial Temperature (supercritical)

Comparing Ex-1L and Ex-1H, the influence of thermal property of water, i.e. specific enthalpy, can be evaluated. Comparing Ex-1L and Ex-2L, and also Ex-1H and Ex-2H, influence of flow properties can be observed.
The quantity of water is unified as 1 kg/s for all calculations.

5. RESULT AND DISCUSSIONS

Changes of thermal output from the reservoir and temperature distribution of the reservoir are calculated for 10 years. Figure 6 shows the changes of temperature difference between the injection and production water with time. Temperature drop is faster in supercritical reservoir (high initial temperature condition) than in non-supercritical reservoir. This may be because heat capacity of water near critical point is relatively high, and therefore, thermal energy of rock is swept rapidly. Although the difference in the results between Model-1 and Model-2 is not significant, treating density and viscosity of water as functions of temperature and pressure makes temperature drop faster for supercritical reservoir and slower for non-supercritical reservoir. However the differences are small.

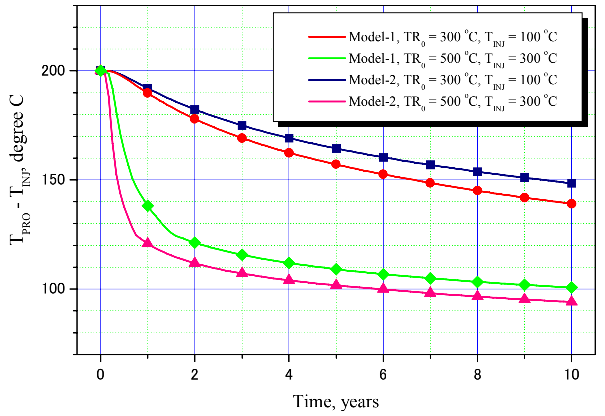

Figure 6. Draw down of production water temperature during 10 years heat extraction for Ex-1L, Ex-1H, Ex-2L and Ex-2H.

The changes of thermal output energy with time, calculated as follows, are shown in Figure 7.

$Q \times$ (Specific enthalpy of production water - Specific enthalpy of injection water)

In contrast to temperature drop, thermal output from supercritical reservoir is larger than that from non-supercritical reservoir. This means that the difference of enthalpy between the injection and production water of supercritical reservoir is larger than that of non-supercritical reservoir, even though the difference of temperature between injection and production water of supercritical reservoir is smaller. Similar to temperature drop, treating water properties as functions of temperature and pressure makes thermal output draw down faster for supercritical reservoir and slower for non-supercritical reservoir.

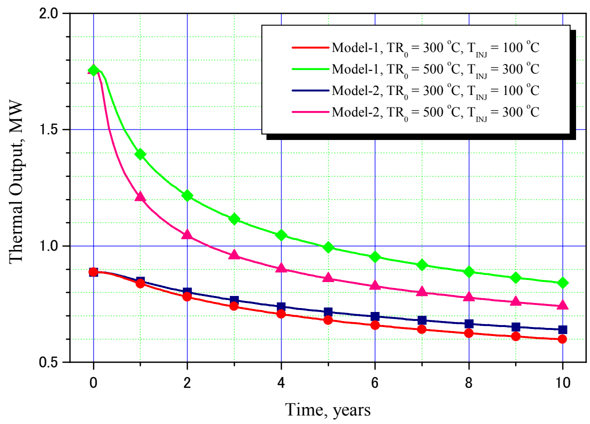

Figure 7. Change of thermal output during 10 years heat extraction for Ex-1L, Ex-1H, Ex-2L and Ex-2H.

Distribution of temperature change at fracture surface after 10 years heat extraction for each analysis are shown in Figure 8 ~ Figure 11. The difference of temperature distribution in Figure 8 and Figure 9 expresses the influence of specific enthalpy of water. It is observed that water can sweep thermal energy from wider area in supercritical reservoir. However, this difference becomes small in Model-2, as shown Figure 10 and Figure 11.

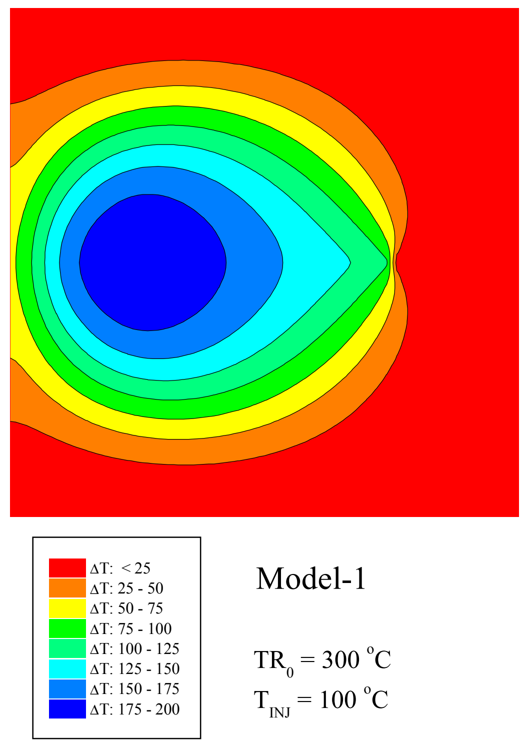

Figure 8. Temperature change at fracture surface after 10 years heat extraction for Ex-1L.

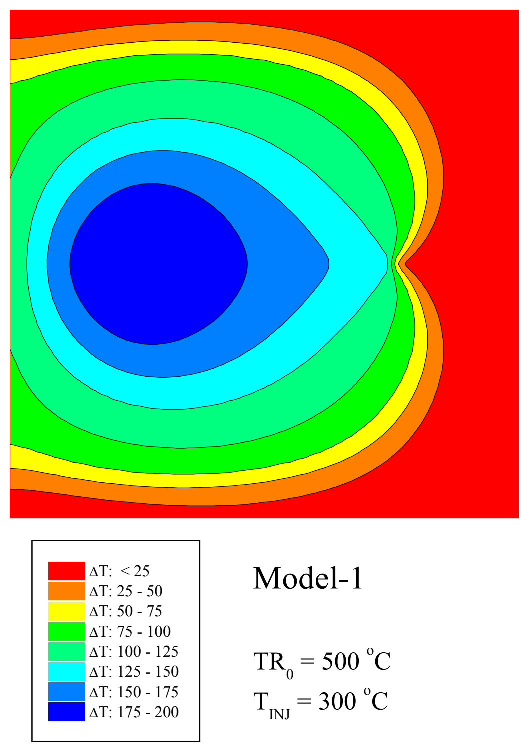

Figure 9. Temperature change at fracture surface after 10 years heat extraction for Ex-1H.

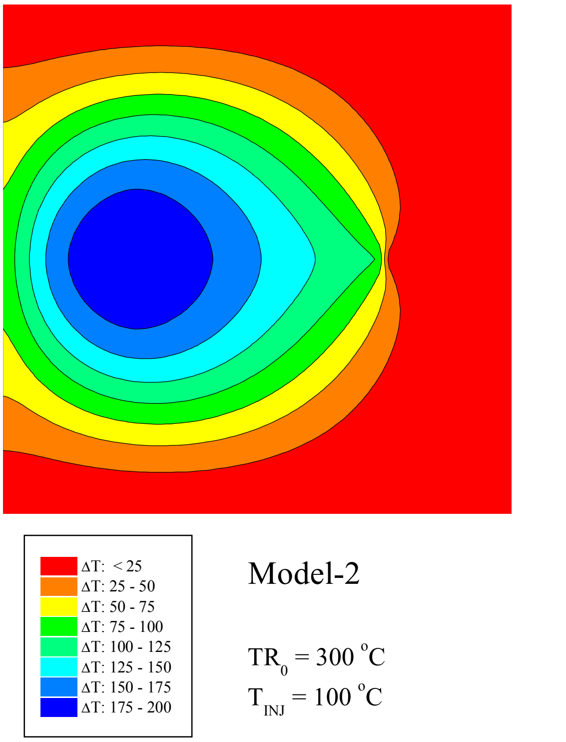

Figure 10. Temperature change at fracture surface after 10 years heat extraction for Ex-2L.

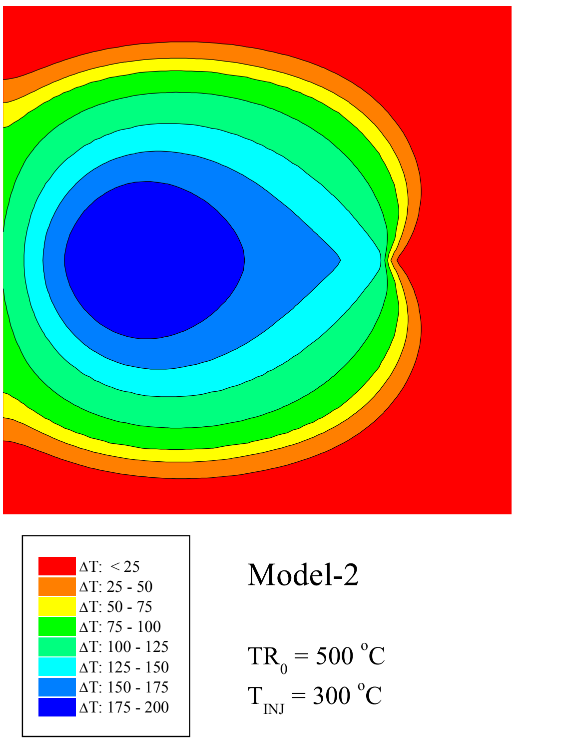

Figure 11. Temperature change at fracture surface after 10 years heat extraction for Ex-2H.

6. CONCLUSIONS

For the evaluation of heat extraction from supercritical HDR/HWR reservoirs, changes of water properties near critical point affect the thermal energy output. Due to high heat capacity of water at critical temperature, it can sweep thermal energy more efficiently from supercritical reservoirs, though production water temperature drops quickly. Changes of density and viscosity of water influence the heat extraction. To evaluate flow properties more accurately, fracture aperture response against water temperature and pressure must be investigated as well as the consideration of flow boundary condition. When the proper design is achieved, supercritical HDR/HWR heat extraction systems are worth to develop.

ACKNOWLEDGEMENTS

The work presented in this paper is supported by the Japan Society for the Promotion of Science under Grant-in-Aid for Research for the Future Program (JSPS-RFTF 97P00901).

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