Simulation Study of a Downhole Heat Exchanger With Thermal Conduction in a Rock Mass for a Small-Scale Power Generation System

Asada Yamato[1], M. Kato[2], and K. Sato[3]

[1]Graduate School of Engineering, Hokkaido University
[2]Faculty of Engineering, Hokkaido University
[3]Nippon COMSYS Corporation

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ABSTRACT

In geothermal development, the development cost mainly comprises the drilling cost. There is no guarantee that steam will be produced even if the drilling is successful. However, the underground rock mass is often at high temperature even if geothermal fluid does not discharge from the well. Therefore, for the well that has little steam discharge, the present study considers a borehole heat exchanger that uses a low-cost, compact and spiral heat collecting tube. Such heat extracting technology does not require a natural geothermal fluid. As the first step of investigation of this technology, we conduct a numerical analysis to evaluate whether we can effectively and continuously exploit heat conducted from the neighborhood bedrock with a heat exchanger.

1. Introduction

According to a nationwide geothermal investigation, Japan has geothermal resources amounting to 23,470 MW per year (Ehara, 2009). Current geothermal power generation is approximately 537 MW per year; thus, only 2.3% of the total geothermal resource is used for the generation of geothermal power. The low utilization of this large geothermal resource is due to the long development period and high development costs, including the cost of drilling wells.

Additionally, there is the concern that large-scale development will negatively affect the landscape and ecosystems, and problems arise when making agreements with owners of hot springs. Additionally, there is no guarantee of success when boring a new well. Indeed, the probability that much steam exits a well is low. The success rate for a well dug in a wide area of investigation is 20%, while that for a well dug in a precise investigation is 67% (Miyazaki, 2009). One-third of wells bored in a close investigation and four-fifths of wells bored in a wide investigation are converted to reinjection or observation wells or are backfilled, and the boring expense is thus wasted.

There is usually high-temperature bedrock near a well even if the well produces little steam. Conventional geothermal power generation operates turbines using natural steam. When

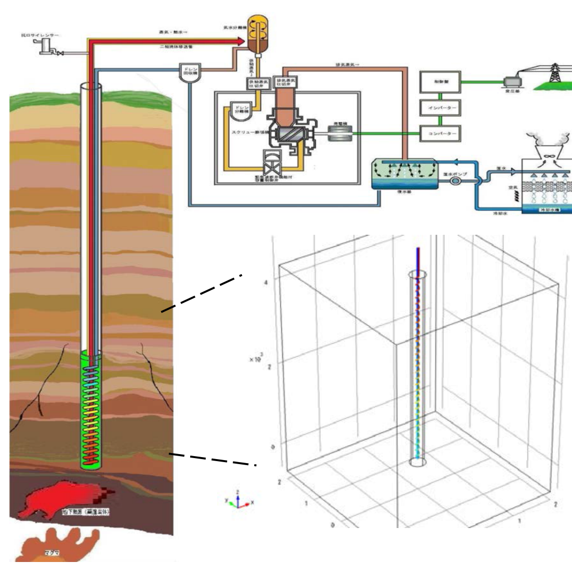

Figure 1. Numerical analysis and the generation system (Kato, 2015).

using natural steam, many problems arise, especially the scaling and corrosion of the turbine material. The present study develops a borehole heat exchanger using a low-cost, compact, and spiral heat collecting tube. We can use this heat exchanger in a well that produces little steam, while hardly affecting the surroundings of the well. Furthermore, there is no possibility of scaling because no geothermal fluid is needed. We plan to use the heat taken from underground to generate electricity. Accordingly, this study develops a heat exchanger that exploits heat from hot bedrock effectively and sustainably.

2. Features of the Heat-Conduction Downhole Heat Exchange System

2.1 Overview of Heat Exchange Systems

Figure 1 presents an example of numerical analysis and a generation system. The heat exchange part has a heat collecting pipe with a spiral shape. However, in this calculation, the heat collecting pipe is straight. The appropriate shape will be determined by numerical analysis. Geothermal power generation usually produces electricity using natural steam. In this system, we generate electricity using circulating water, and we can use this heat exchange system in a well that produces little steam. The power generation system is shown at the upper right of Fig. 1.

2.2 Problems of Scaling and Corrosion

The proposed system does not suffer the problems of scaling and corrosion because natural steam is not used in the equipment. Corrosion may occur on the outside of the casing pipe of the well. Additionally, there is the possibility of precipitation in the pores of reservoir rocks, which would reduce the thermal conductivity. However, because the thermal conductivity of the rocks is originally low, for the system as a whole the effect of the reduced thermal conductivity is small.

2.3 Effects on the Surroundings of the Well

(a) Hydraulic Effect

The proposed system does not directly use geothermal fluid. There is thus no possibility of depleting the resource of geothermal fluid.

(b) Thermal Effect

In the proposed system, heat is mainly obtained by heat conduction from the neighboring bedrock. There is thus a temperature drop only near the well. The temperature distribution produced by heat conduction of the bedrock is shown in Fig. 2. The figure shows the temperature distribution of underground rock around the well in the steady state when the temperature of the well remains at 20 °C. These results demonstrate that the temperature drops only in the immediate surroundings of the well.

(c) Effect on the Landscape and Ecosystem

The proposed system of geothermal power generation requires only small ground facilities. Facilities can thus be designed taking into consideration the landscape and ecosystem.

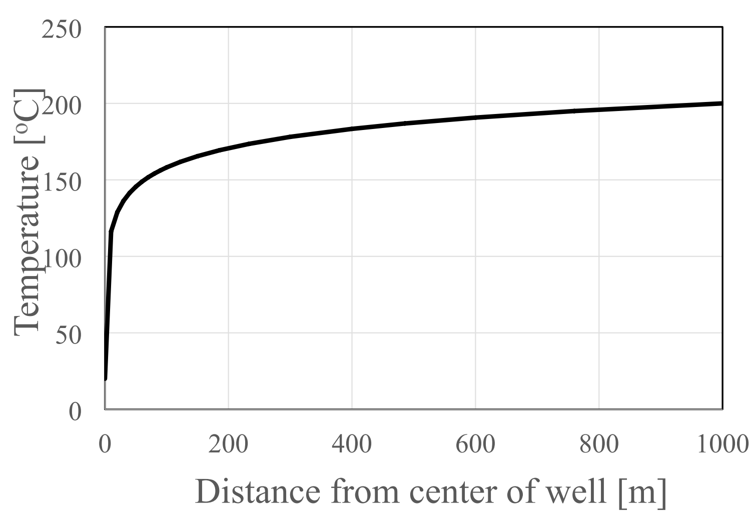

Figure 2. Temperature distribution of underground rock around the well in a steady state when the temperature of the well remains at 20 °C.

2.4 Thermal Output

The average heat output per well at a domestic geothermal power plant is 1115 kW. The goal of the present study is to develop heat exchangers that have a thermal output of 300–500 kW.

2.5 Economy

Using the proposed system, wells that produce little steam bored in geothermal fields can be utilized. In contrast, the drilling cost is wasted when a well that produces little steam is backfilled. Therefore, if half the heat output by a typical geothermal well can be obtained from such a well, there is a large financial benefit to the power station.

3. Finite Element Analysis

3.1 Governing Equations

The present study uses simple governing equations for an incompressible fluid flowing in a pipe and an energy equation for an incompressible fluid flowing in a pipe, as well as the energy equation for the fluid in the well and an energy equation for bedrock. The momentum and continuity equations for flow in a pipe are given by equations (3-1) and (3-2).

$$\rho\frac{\partial u}{\partial t}+\rho u\cdot\nabla u=-\nabla\rho-fD\frac{\rho}{2dh}\ u|u|+|u|+F \tag{3-1}$$

$$\frac{\partial A\rho}{\partial t}+\nabla\cdot(A\rho u)=0 \tag{3-2}$$

The second term on the right-hand side of Equation 3-1 represents the pressure drop due to viscous shearing. Here, u is the cross-section-averaged velocity (m/s), ρ is the density (kg/m^3), p is the pressure (Pa), f_D (dimensionless) is the Darcy friction factor, **F** is a volume force term (N/m^3) and dh is the mean hydraulic diameter (m).

The energy equation for an incompressible fluid flowing in a pipe is given by equation (3-3).

$$\rho ACp\frac{\partial T}{\partial t}+\rho AC\rho u\cdot\nabla T=\nabla\cdot Ak\nabla T+fd\frac{\rho A}{2dh}|u|3+Q+Qwall+Qp. \tag{3-3}$$

Here, ρ is the fluid density (kg/m^3), A is the pipe cross section area (m^2) available for flow, C_p (J/(kg·K)) is the heat capacity at constant pressure, T (K) is the temperature, u is the velocity field and k (W/(m·K)) is the thermal conductivity. The second term on the right-hand side corresponds to friction heat dissipated due to viscous shearing. Q (W/m) is a general heat source and Q_{wall} (W/m) represents external heat exchange through the pipe wall. The energy equation for bedrock is given by equations (3-4) and (3-5).

$$\rho Cp\ \frac{\partial T}{\partial t}+\frac{\partial T}{\partial t}+\rho Cpu\cdot\nabla T+\nabla\cdot q=Q \tag{3-4}$$

$$q=-k\nabla T \tag{3-5}$$

Here, ρ (kg/m^3) is the solid density, Cp (J/ (kg·K)) is the solid heat capacity at constant pressure, k (W/(m·K)) is the solid thermal conductivity (a scalar or a tensor if the thermal conductivity is anisotropic), u(m/s) is the velocity, and Q (W/m^3) is the heat source.

3.2 Boundary Conditions

(a) Pipe Fluid

We treat the inflow border as a waterway entrance and have uniform flow in the Z direction. We treat the outflow border as a waterway exit and give a pressure boundary condition. The wall surface border is assumed to have a non-slip condition, which means the tangential velocity and the direction normal speed at the boundary surface of the object are both zero.

(b) Bedrock

As a boundary condition, we keep the temperature of the side of the bedrock constant.

3.3 Three-Dimensional Numerical Analysis

(a) Summary of the Analysis Model

The present analysis considers the bedrock, well, and mass flow.

The pipe has a U-shape, is 500 m in height and is 48.6 mm in diameter.

The material of the pipe is assumed to be copper with thermal conductivity of 400 W/mK. The pipe thickness is 0.005 m. The well is cylindrical, is 219.1 mm in diameter and is 500 m deep. This study does not consider convection in the well.

The fluid in the well is assumed to be water. The bedrock is assumed to be a rectangular solid having the dimensions 1000 m × 1000 m × 1000 m. We assume the constituent material of the bedrock to be granite. Figures 3 present an overview of the analysis model. Table 1 summarizes the mesh of the analysis model. Table 2 and Fig.4 give the constituent materials

Table 1. Summary of the mesh of the analysis model.

Maximum element size	100
Smallest element size	18
Curvature factor	0.6
Narrow domain resolution	0.5
Edge number of element	353
Border number of element	2112
Number of element	169552
Maxium element growth rate	1.5

Table 2. Constituent materials.

Circulating fluid-well water fluid
Bedrock
Pipe
Water
Granite
Copper

Table 3. Physical properties of granite.

specific heat	850 [J/kgK]
Density	2600 [kg/m³]
Thermal conductivity	2.9 [W/(mK)]

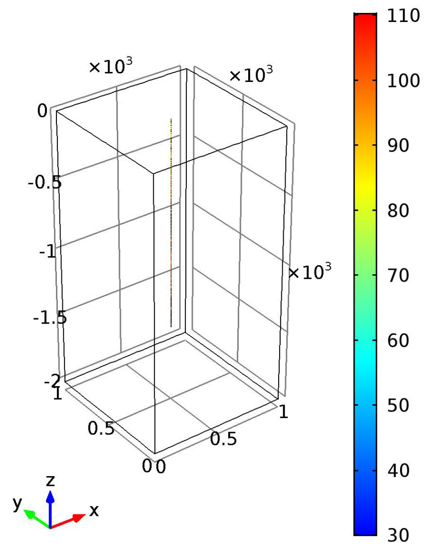

Figure 3. Summary of the analysis.

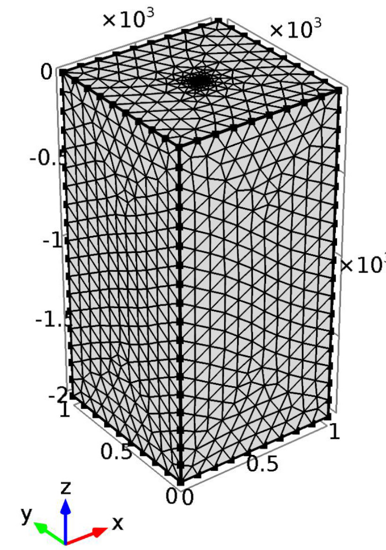

Figure 4. Mesh.

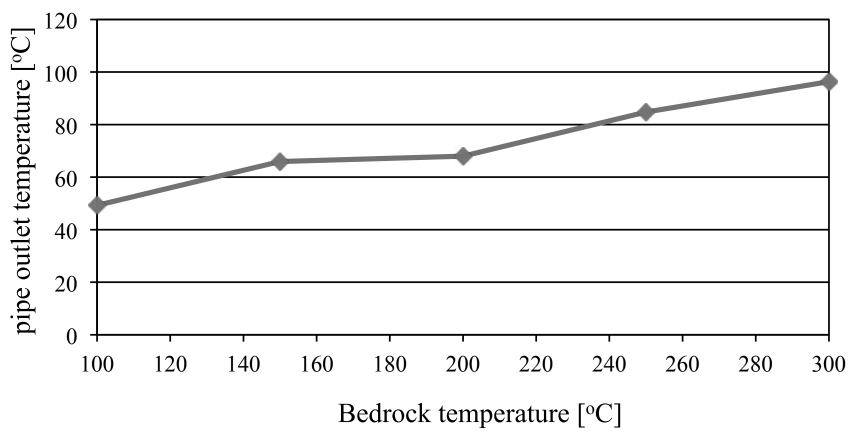

Figure 5. Relationship of the bedrock and outlet temperatures.

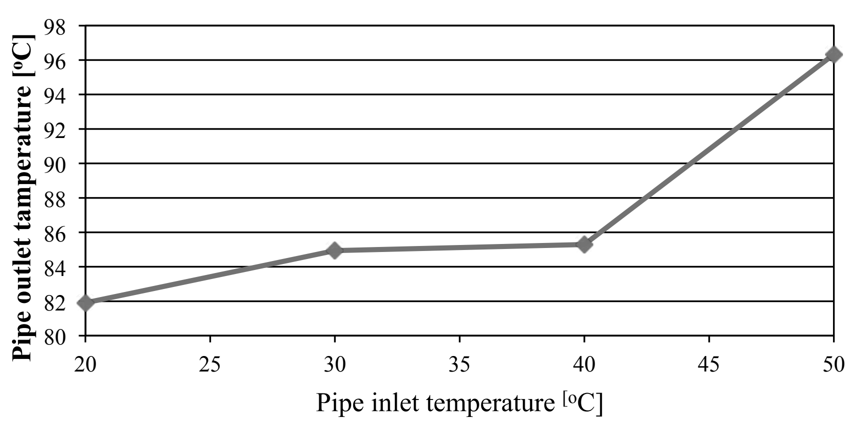

Figure 6. Relationship of the inlet and outlet temperatures.

of the mesh of the analysis model. Table 3 gives the physical properties of granite.

4. Results

We performed a numerical analysis under various conditions to check the validity of the proposed heat exchange system. Results are presented in Figures 6 and 7. The Galerkin finite element method was used in the three-dimensional numerical simulation. The governing equations used here are equations (3-1) to (3-4). Figure 5 presents the relationship of the bedrock and outlet temperatures, while Fig. 6 presents the relationship of the inlet and outlet temperatures.

5. Discussion and Concluding Remarks

We conducted a numerical analysis of the validity of the proposed heat exchange system using a simple model, as part of our development of a borehole heat exchanger having a low-cost, compact and spiral heat collecting tube. The results presented in Fig. 6 show that when the inlet temperature is 50 °C, the outlet temperature is about 120 °C and there is the potential for power generation. The rock boundary temperature was set to 200 °C since we are considering the use of this system in deep geothermal wells. The results obtained thus indicate the validity of the system.

The use of geothermal resources has been studied in deep wells at more than 2000 m depth in Japan. Such wells are said to have twice the geothermal resources of shallow wells. However, various problems arise when generating power from geothermal fluid. The high temperature of the geothermal fluid causes problems such as corrosion of the well and piping. We can avoid such problems by using the proposed system.

On the basis of the results obtained in the present numerical analysis, and feedback on the design and manufacture of the heat exchanger, we will carry out a demonstration test using an actual well as part of future work.

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