Geothermal Resources Council TRANSACTIONS, VOL 9 - PART I, August 1985

DOWN-HOLE COAXIAL HEAT EXCHANGER USING INSULATED INNER PIPE FOR MAXIMUM HEAT EXTRACTION

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ABSTRACT

A detailed study on a down-hole coaxial heat exchanger has been carried out using a numerical simulator for a simplified model of a well. The dependence of the thermal output on certain parameters, such as degree of thermal insulation of the inner pipe, flow rate, inlet water temperature, geothermal gradient and well depth is evaluated. The main result is that an insulating inner pipe could increase thermal output significantly in comparison with a steel inner pipe.

INTRODUCTION

It is generally recognized that there is no less possibility of finding a hot, "dry" geothermal resource than that of a natural geothermal reservoir ("wet" geothermal resource) which is suitable for power generation or multipurpose utilization. Here "dry" geothermal resources are referred to such subsurface conditions in which formation productivity is not high enough to produce sufficient amount of hot-water or water vapor to be used for power generation or direct uses, or in which no production of fluid from the formation is possible at all.

The purpose of this work is to illustrate that there is a method to exploit hot,"dry" geothermal resources by a single well which penetrates in non-producible high temperature formations. The basic idea of this system is a modification of the down-hole coaxial heat extraction scheme discussed in detail by Horne(1980), but the difference of our system from his system is that a thermal insulator is used for the inner pipe down through the bottom of a well, so that we could maximize the energy extraction from the well. A similar field experiment has been attempted by Kurasawa et al.(1981) for a water circulation duration up to 120 hours , although they did not interpret their results correctly. In the present report, using a numerical simulator we demonstrate that a single well reverse flow system with an insulator as inner pipe can produce much higher thermal output than that with conventional steel inner pipe. Results of several model simulation runs are presented to show the long-term change of thermal output of the system as a function of time.

As the first step, the thermal energy extracted by this system will be limited to direct use such as space heating, agricultural and industrial purposes. However, we consider it worthwhile to explore the applicability of this system to small-scale power generation, which might be justified for economical use on an island where geothermal gradient is higher than normal and fuel supply for a power plant is very costly, for example.

NUMERICAL SIMULATOR

The computer code used in this work is the same as that developed by Morita et al.(1984) which is employing explicit solution method to solve finite difference equations on mass and heat transfer in a wellbore and its surrounding formation.

The computer code has been verified by comparing with an analytical solution of a problem given by Carslaw and Jaeger(1959). Comparison of the computed results was also made with the field data of a single well circulation experiment at Yakedake. Good agreement between them were obtained. Physical assumptions of the simulator used in this work are as follows:
1) Heat is transferred only by conduction in the formation.
2) Vertical component of thermal conduction is neglected in the formation, and only the flowing water transports heat vertically by mass movement.
3) Water is assumed incompressible and the energy balance for a water mass can be written by the following formula:

$$dE = dQ + dF/j$$

where E is internal energy of a water mass, dQ is net thermal energy input from wellbore wall and the inner pipe, and F/j is the thermal energy gain due to friction by moving water in the wellbore. Friction along the straight portion of the well is only considered. Temperature dependence of physical properties of water is taken into account at every time step of the simulation.

4) Water is always pressurized so that no vapor phase is present in the wellbore.
5) For the heat balance calculation between water within the inner pipe and water in the annulus, heat capacity of the inner pipe itself can be neglected.

MODEL STUDY

Geometry of the well is shown in Fig.1. In the field, wells are mostly cased with steel pipes of progressively smaller diameters down the hole. In the present study, however, only one wellbore diameter from top to bottom is employed and thermal effect by casing and cementing is not considered. Diameter of the well is 215.9 mm (8 1/2 ") for all models in this study, because the majority of production wells in Japanese geothermal fields are completed with this diameter at the last stage of drilling. For the inner and outer diameters of the inner pipe, 76.2 and 127.0 mm (3 and 5 ") are always specified.

There are two modes of flow of water in the wellbore, forward and reverse flows. "Forward" flow means the way in which water flows down the inner pipe and backs up the annulus. Horne(1980) has shown that reverse flow is somewhat advantageous in extracting energy from the formation. We also obtained a similar results from a comparison between forward and reverse flows. If we are concerned with heat extraction using a single well, it is better to get heat from the entire column of the well in order to increase the total thermal output which we recover at the wellhead. In other words, heat extraction should be made not only from high temperature, deeper part of the formation, but also from lower temperature, shallower part. In the case of reverse flow, heat extraction is performed in such a way and heat loss to the formation is smaller than in the case of forward flow. Therefore, all the simulation runs which we are discussing below are made for reverse flow as indicated in Fig.1. Physical properties of the formation representing granitic rocks is used as listed in Table 1.

RESULTS

A) Effect of Insulating Inner Pipe on Thermal Output (Simulations L1 to L4)

Simulations were made by changing λ (thermal conductivity of the inner pipe) in an attempt to establish the dependence of net heat extraction rate(denoted HER below) at the surface on the degree of insulation of the inner pipe. Four different values of λ, 0.01, 0.1, 1.0, 39.6 Kcal/m h°C, were used and we denote these runs as L1, L2, L3, and L4, respectively. Following values of other parameters were specified:

Total depth of the system (wellbore and inner pipe)	3000 m
Ground surface temperature	15°C
Inlet water temperature	15°C
Undisturbed geothermal gradient	111.7°C/km
Volumetric flow rate	0.3 m^3/min

We set the lowest value as $\lambda = 0.01$, because it corresponds to the thermal conductivity of conventional insulated pipes for surface

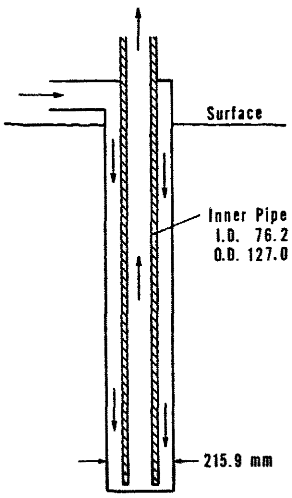

Fig.1. Configuration of the simulation model

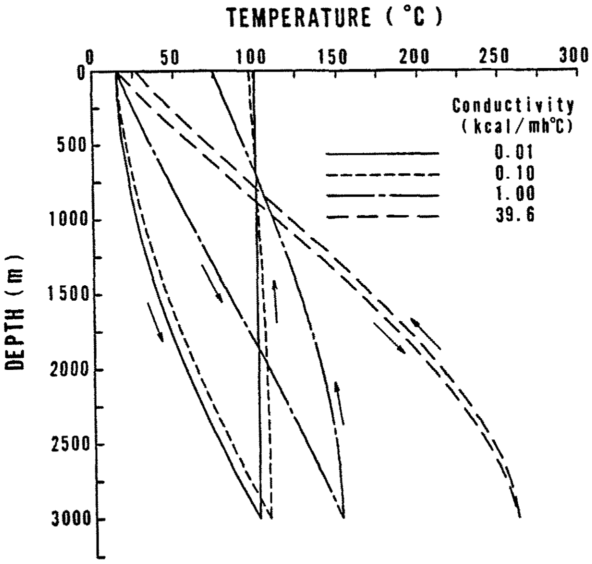

Fig.2. Effect of thermal conductivity of inner pipe on temperature distribution in the well (circulation period : 1 yr)

installation. The highest one 39.6 represents the thermal conductivity of ordinary steel pipes.

The Temperature distribution in the wellbore after a circulation period of one year from the beginning of circulation(t= 1 yr) is shown in Fig.2. In Table 2, HER and outlet water temperature (denoted Tout below) are summarized for L1 through L4 experiments. As clearly demonstrated by these results, energy extraction rate is larger and outlet temperature is higher with smaller value of λ . If the best insulating inner pipe with λ = 0.01 is adopted, HER at t = 1 yr is approximately 7.4 times as high as that using a steel inner pipe. Tout is higher by 74°C. The difference of HER between the cases of λ= 0.1 and λ= 0.01 is rather small. It can be seen in Fig.2 that the temperature difference between the water in the annulus and that in the inner pipe is greater for a smaller value of thermal conductivity of inner pipe. When λ is small, the pressure of the annulus becomes higher than that of the inner pipe due to the difference of water density. We can expect less power to circulate water in the system. The reason of increase of HER may be that insulated inner pipe is keeping the water in the annulus from being warmed up by the hot water within the inner pipe, so that larger temperature difference between the wellbore surface and the water in the annulus can be maintained than in the case with a steel inner pipe. And heated water comes up from the bottom to the surface through the inner pipe without cooling.

From these results, effect of an insulated inner pipe on the enhancement of HER and Tout is apparent. Therefore, we will use λ=0.01 for the thermal conductivity of the inner pipe for all the following simulations.

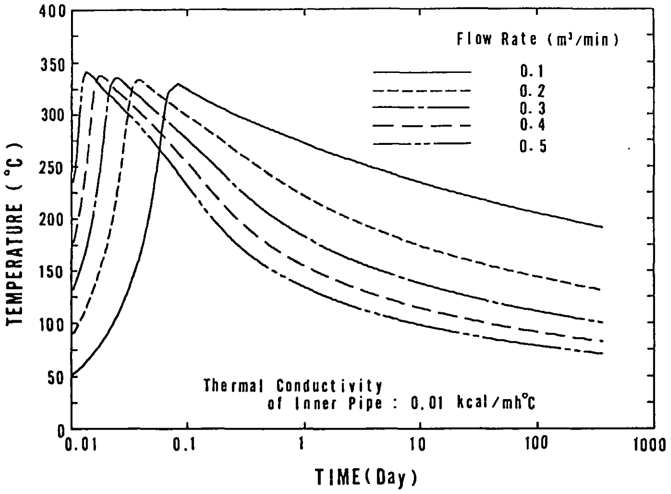

Fig.3. Variation of outlet water temperature with time

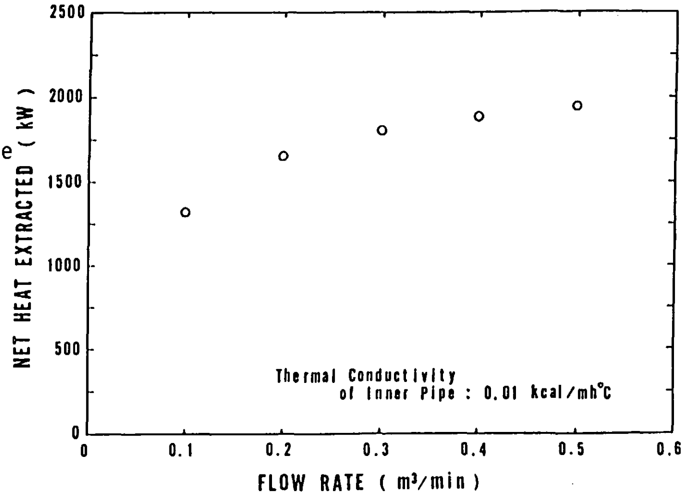

Fig.4. Dependence of heat extraction rate at t = 1 yr on flow rate

B) Heat Extraction Rate and Wellhead Outlet Temperature for Various Values of Flow Rate (Simulations A1 to A5)

The effect of flow rates on HER and Tout are studied by specifying physical conditions the same as those in the above section, except flow rate and thermal conductivity of inner pipe. The flow rates studied are 0.1, 0.2, 0.3, 0.4 and 0.5 m^3/min, which are denoted as A1 to A5, respectively. The results of these simulations are shown in Fig.3, in terms of the time change of Tout. We summarize these results at t= 1 yr in Table 3. As shown in Fig.3, Tout is characterized by the presence of a peak and subsequent gradual decrease. As the decreasing rate of Tout becomes smaller with time, it can be inferred that the difference of Tout between at t = 1 yr and t = 10 yrs is small. The change of HER with time is very similar to that of Tout.

Tout value decreases with increasing flow rate. On the other hand, HER at t = 1 yr for a flow rate of 0.5 m^3/min is higher by a factor of 1.5 than that of 0.1 m^3/ min and higher flow rate generally corresponds to higher HER. As can be seen in Fig.4, however, there seems to be a critical value of HER. HER may not be increased than this value even for a much higher flow rate.

C) Effect of Geothermal Gradient and Well Depth (Simulations G1 to G11)

Effect of geothermal gradient and well depth on HER and Tout are studied by specifying the flow rate at 0.3 m^3/min. Geometry of the well and the physical conditions other than the geothermal gradient and the well depth are the same as the simulation L1. Fig.5 shows the relation between geothermal gradient and HER at t = 1 yr. For a constant depth of the well, value of HER increases linearly with increasing geothermal gradient. For a constant geothermal gradient, HER increases with the well depth. It should be remarked here that the flow rate is kept constant at 0.3 m^3/min in Fig.5. If the flow rate is larger than that, somewhat higher heat extraction rate is attainable, as already discussed above.

D) Effect of Inlet Water Temperature

HER and Tout were studied by changing the value of inlet water temperature(Tin); 30, 45, 60, and 75 ℃(denoted T1 to T4). Physical conditions except Tin and λ are the same as those in the series L1 to L4.

When Tin is higher than the ground surface temperature, there is a heat loss from the water in the annulus to the formation. It may be effective to install an insulated casing for the portion of the well where such heat loss is expected. Hence, simulation runs were also made for the cases in which insulated casing are set from the surface to depths of 100, 300, 400 and 500 m for the values of Tin, 30, 45, 60, and 75 (denoted TC1 to TC4), respectively. These depths of casing shoe correspond to the depths where water temperature in the annulus is close to the formation temperature. Thermal conductivity, specific heat, and specific weight of the insulated casing are assumed as 0.01 k cal/ m h ℃, 0.112 k cal/ kg℃, and 7850 kg/m^3. Here we employ the same values of specific heat and specific weight as those of a steel pipe, since these parameters do not affect the long-term thermal behavior of the system. Inner and outer diameters of the casing are 215.9 and 266.7 mm (8 1/2 and 10 1/2 ") and the thermal effect due to cementing behind the casing is not taken into account.

Table 4 summarizes the results of T1 to T4 as well as TC1 to TC4 simulations in terms of HER and Tout at t = 1 yr. HER is significantly reduced by the increase of inlet water temperature. This observation is not the same as that reported by Horne(1980). As shown in Table 4, Tout becomes higher for a higher value of Tin. Outlet water temperature changes only a little more than a half of the change of Tin, however. The effect of insulated casing is relatively small. Only about 2.5 % increase in HER in comparison with the case without the insulated casing is observed for a condition of Tin = 75℃.

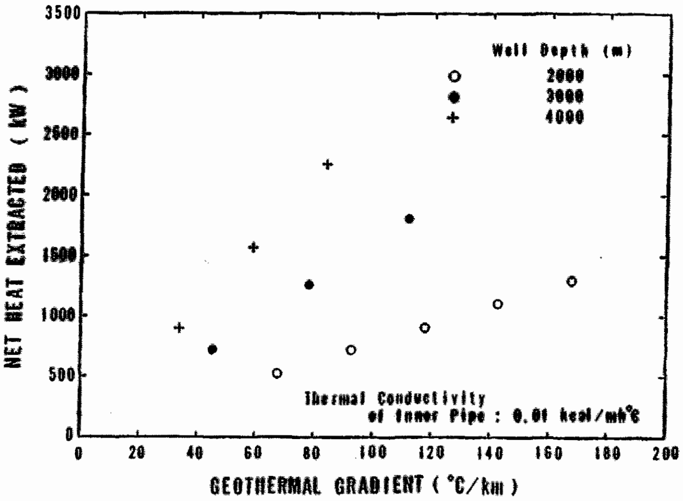

Fig.5. Net heat extraction rates as a function of geothermal gradient (circulation period: 1 yr)

CONCLUSIONS

(1) By using an insulated inner pipe, thermal output of a down-hole coaxial heat exchanger could be significantly increased.

(2) As Horne(1980) pointed out, we also recommend reverse flow as a method for recovering maximum heat extraction from a single well.

(3) If the depth of a well is constant, thermal output of the system increases proportionally with increasing geothermal gradient. If geothermal gradient is constant, the thermal output is larger for larger value of well depth.

(4) For higher inlet water temperature, net heat extraction rate becomes smaller and outlet water temperature becomes higher but its increase is not so large as the increase of inlet temperature. Effect of an insulated casing for preventing heat loss to the formation is rather small when the inlet temperature is higher than the ground surface temperature.

The heat extraction rate obtained in the present work might not seem large enough from the economical point of view. We would like to emphasize that in our work only thermal conduction is considered as the heat transport mechanism in the formation. However, as Horne(1980) mentioned, the heat extraction rate could be greater than we have shown above, because in most cases heat may be transferred to the well convectively also. Results of the Lava Lake Heat Extraction Experiment also indicate such a possibility (Colp, 1982). Therefore, hydraulic fracturing as a technique to enhance the formation permeability may help increase the heat extraction rate significantly.

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Table 1 Properties of formation

Density kg/m^3	Specific Heat kcal/Kg °C	Thermal Conductivity kcal/mh °C
2,600	0.2	2.7

Table 2 Thermal Output as a Function of Thermal Conductivity of Inner Pipe
Circulation Period : 1 Year

Thermal Conductivity (kcal/mh°C)	0.01	0.10	1.00	39.6
Net Heat Extraction Rate (kW)	1,799	1,728	1,248	244
Outlet Water Temperature (°C)	100.4	97.0	74.6	26.7

Table 3 Effect of Volumetric Flow Rate on Thermal Output
Circulation Period : 1 Year
Upper : Net Heat Extraction Rate (kW)
Lower : Outlet Water Temperature (°C)

	Volumetric Flow Rate (m^3/min)				
	0.1	0.2	0.3	0.4	0.5
Thermal Output	1,317	1,649	1,799	1,888	1,945
	191.4	130.9	100.4	82.4	70.7

Table 4 Effect of Utilizing Insulated Casing on Thermal Output for Various Inlet Water Temperature
Circulation Period : 1 Year
Upper : Net Heat Extraction Rate (kW)
Lower : Outlet Water Temperature (°C)

Casing	**Inlet Water Temperature (°C)**			
	30.0	45.0	60.0	75.0
No Casing	**1,664**	**1,530**	**1,395**	**1,259**
	108.7	117.2	125.7	134.1
Insulated (0.01 kcal/mh°C)	1,666	1,536	1,410	1,291
	108.8	117.5	126.4	135.6