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FEASIBILITY STUDY OF A HOT DRY ROCK PROJECT IN HUNGARY

The modeling of an artificial geothermal reservoir (HDR) system relies on the proper description of the operation of its three main components: the injection well, the artificial reservoir, and the producing well. In each, different thermal and hydraulic processes take place that have to be described for the modeling of the total system. (Rybach & Muffler, 1981; Armstead & Tester, 1987).

The most important element of the system is the artificially created geothermal reservoir made in an impermeable hot rock body using hydraulic formation fracturing. Present-day formation fracturing technology allows creation of huge fracture surfaces with preferably vertical planes in rock bodies. Fractures thus formed have a limited width through which water can be forced to circulate to the surface in a closed loop. The area of such fractures acts as a heat exchanger through which forced heat convection is maintained by the conductive heat flux from the rock masses. (Brown, 1995; Gringarten et al, 1975)

The hydraulic and thermal processes in the injection well are the downward turbulent flow and heat transfer in the well. They are calculated by properly taking into account the well's inclination data. The basic equations describing heat transfer and pressure drop are basically the same although certain specific assumptions have to be used. The paper contains detailed derivations of the governing equations and shows how these can be used to find the temperature along the depth of the injection well.

Outflowing water at the bottom of the injection well enters the artificial reservoir. The reservoir consists of two parallel plane walls with a constant distance between them. In contrary to porous reservoirs like oil or gas fields, the gross surface area involved is much smaller and the fluid motion is also different. A real laminar or turbulent flow takes place instead of a fluid seepage. During its flow towards the producing well water is warmed up due to the forced convection taking place at the fracture's walls. Using some simplifying assumptions the authors derive a calculation model for the temperature rise of the injected water. The high-temperature water contains the energy extracted from the rock masses. This water is then led to the producing well.

Geothermal energy is transported from the reservoir to the surface through a production well. The hydraulic and thermal processes in the producing well are very similar to those in the injection well. Hot water produced from the artificial reservoir, as it rises to the surface, is continuously cooled by the surrounding rock masses. Finally, water reaches the surface with a lower temperature than that valid at the well bottom. The energy content of this water is removed at the surface and the resulting low-temperature water is re-injected, thus completing a full circle.

In order to investigate the above closed-loop energy recovery system, the authors had to introduce several simplifying assumptions when setting up the physical model.

Before the detailed description of the system components' behavior the most important assumption are listed below:

a) The rock mass where the artificial fractures are formed is homogeneous and isotropic.
b) The permeability of the fracture walls is negligible.
c) The working fluid (water) is incompressible.
d) Water is not assumed to evaporate due to sufficient pressure in the system.
e) The specific heat of the injected water is constant.

MATHEMATICAL MODELING

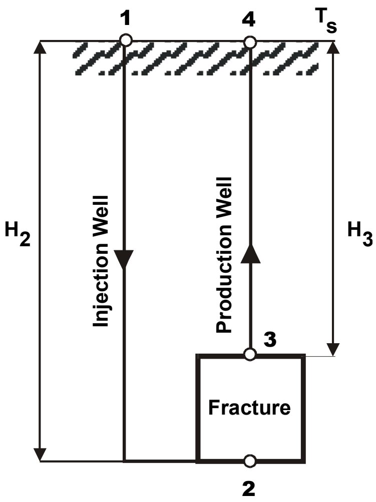

Fig.1. The geometrical arrangement of the investigated system.

In the following sections, each of the three main components of the investigated system will be examined and appropriate mathematical expressions will be derived to model its behavior. Conveniently, the treatment of the individual system elements follows the streamlines of the circulated water as shown schematically in Fig. 1.

The Injection Well

The injection well, as an acceptable simplification, is considered to be a vertical borehole. The heat transfer process in the borehole is a forced convection between the casing string wall and the injected fluid, and an axis-symmetric conduction toward the well in the surrounding rock mass.

The internal energy balance of the fluid can be written for a control volume bounded by the cylindrical surface of the casing string and two horizontal parallel planes at a vertical distance of *dz*, see Fig. 2.

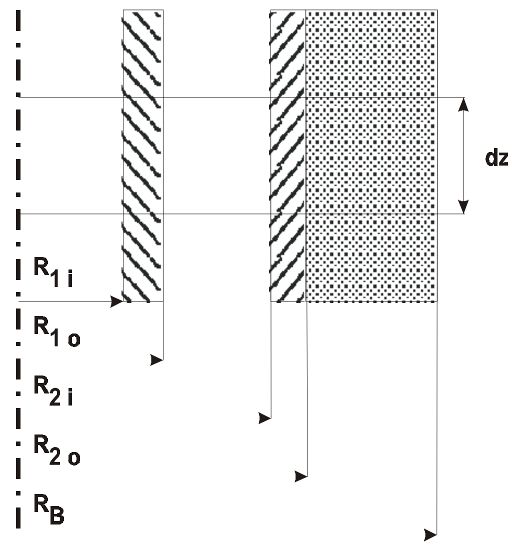

Fig. 2. Control volume for well temperature calculations.

Thus, we get

$$\dot{m}c_f dT_f = 2\pi R_{1i} U_{1i} (T_B - T_f) dz \tag{1}$$

The conduction of heat in the rock mass around the wellbore is expressed as

$$2\pi R_{1i} U_{1i} (T_B - T_f) = \frac{2\pi k_r}{f(t)} (T_\infty - T_B) \tag{2}$$

The undisturbed rock temperature far from the well varies linearly with depth:

$$T_\infty = T_s + \gamma z \tag{3}$$

The transient conductivity factor *f(t)* is the logarithm of the ratio of radius R_∞ of the undisturbed rock temperature and the radius of the wellbore:

$$f(t) = \ln \frac{R_\infty}{R_B} \tag{4}$$

f(t) was experimentally determined by Willhite (1967) based on the Fourier-number and the parameter $R_{1I}\, U_{1i}/k_r$.
Introducing the so-called depth factor (Ramey, 1963)

$$A = \frac{\dot{m}c_f \left(k_r + f(t) R_{1i} U_{1i}\right)}{2\pi R_{1i} U_{1i} k_r} \tag{5}$$

the temperature distribution along the well depth is found:

$$T_f = T_s + \gamma(z - A) + (T_1 - T_s + \gamma A) e^{\frac{z}{A}} \tag{6}$$

From this, fluid temperature at the bottom of the injection well is calculated from the formula below which also gives the temperature of the injected fluid at its entrance to the artificial fracture. (See point 2 in Fig. 1)

$$T_2 = T_s + \gamma(H - A) + (T_1 - T_s + \gamma A) e^{\frac{H}{A}} \tag{7}$$

The Artificial Reservoir

The most important element of the investigated geothermal system is the downhole fracture acting as a heat exchanger. This is assumed to be bounded by parallel plane walls with a constant distance between them. In contrast to porous hydrocarbon reservoirs the surface area involved is much smaller and the motion of the injected water is not seepage, but real laminar or turbulent flow. While moving upwards in the fracture the water warms up due to the continuous heat transfer between the fluid and the fracture walls. The heat transfer in the fracture is of the forced convection type, the heat supply being conductive.

In order to describe the hydraulic and heat transfer problems some simplifying assumptions were made:

- the rock mass and the fluid are homogeneous with uniform material properties,
- the orientation of the fracture system is vertical,
- the shape of the fractures is rectangular,
- fracture faces are separated by a constant distance,
- fluid flow in the fracture system is steady-state, laminar, vertical upward flow,
- the conductive heat flux in the fluid is negligibly small.

The actual shape of the fracture is, of course, unknown and only an equivalent heat-transfer surface area is used in the calculations. Actual fracture areas have to be estimated from measurements of outflowing water temperatures. (Bobok, 1995)

In order to calculate the temperature distribution in the fracture a control volume is chosen as an infinitesimal volume element bounded by the fracture walls and two parallel horizontal planes with a distance of *dz* between them. Fluid flow in the control volume is uniform and directed upward. An energy balance for the fluid in the control volume element can be written as:

$$-\dot{m}c_f dT_f = 2LU\left(T_\infty - T_f\right)dz \tag{8}$$

In this equation, *U* is the overall heat transfer coefficient representing the heat transfer between the fracture wall and the flowing fluid, as well as the conductive heat flux through the rock mass toward the fracture. The heat flux between the wall and the fluid is:

$$q = h\left(T_w - T_f\right) \tag{9}$$

where h is the heat transfer coefficient between the fracture wall and the fluid.
The unsteady-state linear heat conduction can be described by the following differential equation:

$$\frac{\partial T_r}{\partial t} = \frac{k_r}{\rho_r c_r}\frac{\partial^2 T_r}{\partial x^2} \tag{10}$$

where axis x is perpendicular to the fracture surface.
The boundary conditions are:

$T_r = T_\infty$ if $t = 0$ and $x \neq 0$

$T_r = T_w$ if $t = 0$ and $x = 0$

The solution of Eq. 10, according to Carlslaw & Jaeger (1957) is the following:

$$T_r - T_w = T_\infty - T_w erf\frac{x}{2\sqrt{\frac{k_r t}{\rho_r c_r}}} \tag{11}$$

The heat flux at the fracture wall is:

$$q = -k_r \left.\frac{\partial T}{\partial x}\right|_{x=0} = -k\frac{T_\infty - T_w}{\sqrt{\frac{k_r t}{\rho_r c_r}\pi}} \tag{12}$$

Combining Eqs. 9 and 12 we get:

$$q = \frac{T_\infty - T_f}{\frac{1}{h} + \sqrt{\frac{\pi t}{k_r c_r \rho_r}}} \tag{13}$$

From here, an overall heat transfer coefficient is obtained as:

$$U = \frac{1}{\frac{1}{h} + \sqrt{\frac{\pi t}{k_r c_r \rho_r}}} \tag{15}$$

As seen, heat flux decreases with time. Let us introduce the variable:

$$B = \frac{2LU}{\dot{m}c_f}$$

and solve the inhomogeneous linear differential equation to get the water temperature distribution with vertical distance z:

$$T_f = T_s + \gamma z + \frac{\gamma}{B} - \left(T_s + \gamma H_2 + \frac{\gamma}{B} - T_2 \right) \cdot e^{B(z-H_2)} \tag{15}$$

Form this, the outflow temperature of the water at the top of the fracture is found as:

$$T_3 = T_s + \gamma H_3 + \frac{\gamma}{B} - \left(T_s + \gamma H_2 + \frac{\gamma}{B} - T_2 \right) \cdot e^{B(H_3-H_2)} \tag{16}$$

The Producing Well

Calculation of the temperature distribution of the returning water in the production well is done analogously to the determination of injection well temperature. The only differences are in the direction of the fluid flow and the direction of heat flux.

The balance of internal energy is written analogously to Eqs 1 and 2. The boundary condition is the inflowing fluid temperature T_3, at the bottom of the production well. Thus the temperature distribution in the producing well is:

$$T_f = T_s + \gamma(z - A_p) + \left[T_3 - T_s + \gamma(A_p - H_3)\right] e^{\frac{z-H_3}{A_p}} \tag{17}$$

where A_p is the depth factor for the production well calculated from Eq. 5.

Finally, the outflowing fluid temperature at the production wellhead can be found from:

$$T_4 = T_s - \gamma A_p + \left[T_3 - T_s + \gamma(A_p - H_3)\right] e^{-\frac{H_3}{A_p}} \tag{18}$$

Power Conditions

In the knowledge of the temperature distribution along a streamline in the investigated geothermal system the heat extracted from the rock masses can be found. One can calculate the in-situ thermal power, i.e. the power extracted from the artificial fracture by the following formula:

$$P = \dot{m} c_f (T_3 - T_2) \tag{19}$$

The gross thermal power is found from the mass flow rate and the effective temperature rise of the injected water, measured at the surface. Effective temperature rise is the difference between the surface outflowing and the injection water temperatures. The power calculated this way and given by the equation below disregards any surface temperature losses and the efficiency of the surface heat exchanger.

$$P = \dot{m} c_f (T_4 - T_1) \tag{20}$$

LOCATING A SUITABLE SITE IN HUNGARY

General Requirements

The most important requirement for a project described in this paper is the existence of a hot dry rock body. This should have the following basic features:

- a temperature of at least *200°C*,
- a rock with a permeability of less than 10^{-6} *Darcies*,
- a relatively high heat conductivity value of the rock (*>4 W/mK*), and

- suitability for hydraulic fracturing.

The best rock formations meeting the above criteria are located in areas where both the geothermal gradient and the terrestrial heat flux are high. This is because a high geothermal gradient can significantly reduce the required depth of the wells and the associated drilling costs. It is an added advantage if shale layers with low heat conductivity values cover the target rock formation.

It is also important to know the in-situ state of stress in the hot dry rock. As known, fractures occur at a right angle to the direction of the greatest stress, and perpendicular to the direction of the least main stress determined by tectonic stresses. (Kuger, 1995) The most convenient technique could be to create vertical fractures with a constant spacing along an inclined borehole. By creating several parallel fractures the resulting heat transfer area is increased to such extent which allows a permanent high-capacity heat extraction.

Totkomlos Area

Although no hot dry rock projects took place in the country before, the authors believe in its feasibility. A detailed study of the basement geometry of the Pannonian Basin along with the temperature and lithological data of wells drilled so far have produced interesting facts. It was found that basement rocks at the southeastern part of the Hungarian Plains lie relatively close to the surface. Since the geothermal gradient, as is the case in the whole country, is high, drilling costs to reach the impermeable high-temperature rock can be moderate.

The well Totkomlos-I, situated in the above geographical area seems to be an ideal candidate, since in this hole the Pannonian sedimentary layers have a relatively small thickness. In addition, the features of this well are excellently documented because its core samples were analyzed in hydrocarbon genesis studies. Thus the variation with depth of all necessary parameters like rock heat conductivity, rock temperature, geothermal gradient are known.

SIMULATION RESULTS

After locating a suitable site, the Totkomlos area, in Hungary, several simulation runs were made using the program package developed along the mathematical model developed in this paper. In all calculations, the authors used actual measured physical parameters found in the files of the Totkomlos-I well thus ensuring the accuracy of predictions.

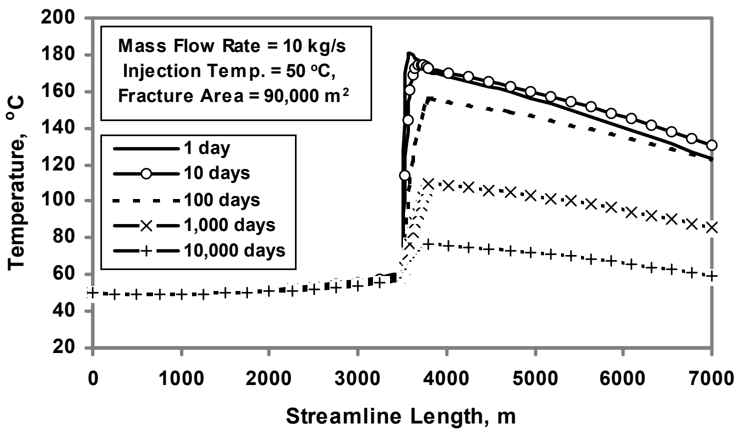

Fig.3. Temperature distribution in the system for a 90,000 m2 fracture and a water mass flow rate of 10 kg/s.

The thermal behavior of the HDR system was simulated over a wide range of conditions. Injection well depth was *3,500m*, the geothermal gradient was taken as *0.05 °C/m*, a rather typical value in the Hungarian Plains area. The size of the artificial fracture was varied between *20,000m²* and *200,000m²* with an assumed fracture width of *8mm*. Water mass flow rates ranged between *5* and *50kg/s*. A surface water injection temperature of *50°C* was assumed.

Simulation runs resulted in detailed temperature distributions along the streamlines in the system of the heat carrying water. Some typical temperature distributions are shown in Figs. 3 and 4.

In the above figures, the different curves are for different system performance times. The first, low slope section of each curve proves that temperature in the injection well does not increase significantly because the surface injection temperature is well above the ambient rock temperature in the well. After entering the artificial fracture, the water is rapidly heated and it attains its maximum temperature at the bottom of the production well. While flowing upward in the production well, the water loses its heat rapidly with an associated decrease of its temperature.

The effect of performance time is easily seen, the longer the period of heat

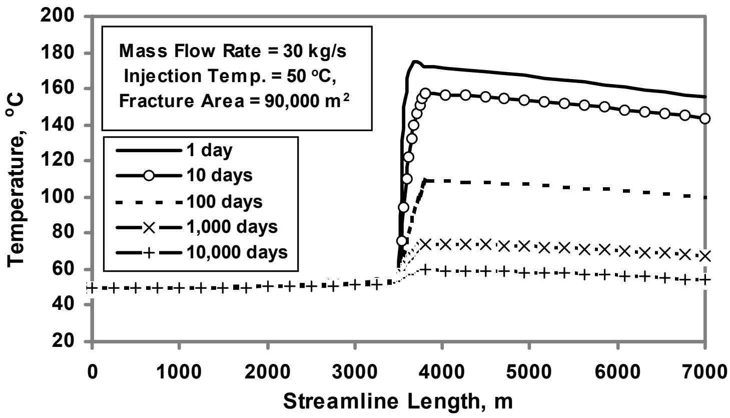

Fig.4. Temperature distribution in the system
for a 90,000 m2 fracture and a water mass flow rate of 30 kg/s.

extraction the lower the reservoir temperature. Because the transient heat flux to the fracture decreases with time, the surface outflow temperature diminishes substantially.

A comparison of our results and those of the first HDR experiment in Los Alamos show a good correlation. There, a *40,000m²* fracture and a mass flow rate of *13.5kg/s* with a downhole temperature of *187°C* provided an outflow temperature of *137°C* on the first day. Water temperature decreased in 75 days to *87°C*. All these numbers are rather close to those found in this study.

The gross thermal power available from the investigated system is shown in Fig. 5. For a constant fracture area, power increases with the mass flow rate of the injected water. Time is an important parameter here, too. For longer operational periods, the output of the system decreases.

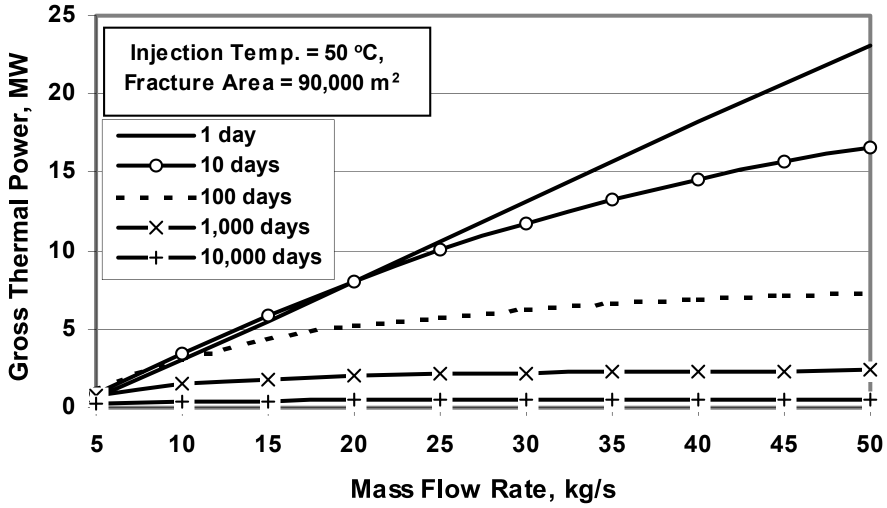

Fig.5. The available gross thermal power
from a 90,000 m2 fracture vs. mass flow rate for different operation times.

CONCLUSIONS

The conclusions of the theoretical work performed by the authors can be summed up as follows.

The natural conditions in Hungary are suitable for geothermal energy production utilizing artificial reservoirs.

The Totkomlos-I well was found to be an excellent candidate to investigate a practical application.

The authors presented the first numerical simulation data supporting this idea.

Further research work is needed to develop a more detailed feasibility study of a HDR project in the proposed region.

SYMBOLS

A depth factor, m
B fracture parameter, 1/m
c_r specific heat of rock, J/kg°C
c_f specific heat of fluid, J/kg°C
γ geothermal gradient, °C/m
h heat transfer coefficient, W/m^2°C
H_2 depth of injection well, m
H_3 depth of production well, m
kr heat conductivity of rock, W/m°C
L fracture length (horizontal), m
m water mass flow rate, kg/s
ρ_r density of rock, kg/m^3
ρ_f density of fluid, kg/m^3
R_{1i} inside radius of tubing, m
R_{10} outside radius of tubing, m
R_{2i} inside radius of casing, m
R_{2i} outside radius of casing, m
R_B radius of borehole, m
R_∞ radius of undisturbed rock temperature, m
t time, s
T_f fluid temperature, °C
T_r rock temperature, °C
T_∞ initial rock temperature, °C
T_s surface ambient temperature, °C
T_1 injection temperature at the surface, °C
T_4 outflowing fluid temperature at the wellhead, °C
U overall heat transfer coefficient, W/m^2°C

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