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ANALYSIS OF THE EXPLOITATION OF EXISTING DEEP PRODUCTION WELLS FOR ACQUIRING GEOTHERMAL ENERGY

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The aim of the work is to assess the possibility and usefulness of acquiring geothermal energy from the existing production well Jachówka K-2. The initial assumptions that are essential for estimation of both a heat flux transferred between a deposit and a heat carrier and a heat flux permeated through the barrier are discussed. To achieve this goal, the authors have worked out a computational model that allowed them to determine the value of the gained geothermal heat flux using a double-pipe geothermal heat exchanger with a dead center. In what follows, the results of calculations of a heat flux that can be gained in the investigated well at a depth L = 2870 m are given.

Introduction. In most cases, geothermal heat plants operate in two-hole systems with injection and production wells. In such systems, the temperature of the geothermal water extracted to the earth's surface as well as the temperature of the water injected onto a deposit level may be estimated to sufficient accuracy with the help of the known computational models in a relatively simple way. When the flows of drawn-out water are great, changes in the temperature of geothermal water in injection and production conductors are relatively low. However, the high expenditure of hole drilling in comparison to the total capital cost is a negative aspect of using this method in acquiring thermal energy. Employment of a one-hole injection system may reduce the capital cost. Drilling of one hole or using existing single holes resulting from rock oil and earth gas extraction is the most effective from the economical point of view. To adapt the hole, a vertical exchanger with a double-pipe exchanger must be located in it. In this case, geothermal water is extracted with the inside pipe and injected into a deposit with a ring-shaped channel.

1. A Double-Pipe Heat Exchanger with a Dead Center. The calculations were done on the assumption that a double-pipe heat exchanger called the Field exchanger is used to obtain the energy held in the earth. The existing casing string of the well serves as the outside frame of the exchanger. The other pipe, of a relatively smaller diameter, located concentrically, is the inside channel of the exchanger. In such an exchanger, the circulating fluid injected into the ring-shaped channel, which is formed by concentric pipes, flows down to the lower part of the exchanger and is gradually warmed up by taking heat from the rocks. At the lower dead center, the fluid reaches the maximum temperature, whose value depends on, among other things, the conditions of the heat exchange as well as the flow rate. Then the fluid flows out through the inside channel to the ground (Fig. 1). Heat exchange takes place both on the outside wall of the exchanger (between the rock and the fluid flowing through the ring-shaped channel) and between the fluid in the ring-shaped channel and the countercurrent fluid flowing through the inside channel of the exchanger.

In considering the possibility of utilizing of the geothermal energy, we studied a 2870-m-long Field exchanger, the casing of which is a column of steel pipes with diameters of 244.5/222.0 mm; a column of pipes with diameters of 60.3/50.7 mm was situated concentrically inside the exchanger [1]. The scheme of the proposed variant of the Field exchanger is given in Fig. 2.

To bound heat exchange between the countercurrent flows of the fluid, the surface of the pipe, which is the inside channel of the exchanger, must be insulated. The following types of insulation were considered in the calculations:

* perfect insulation of the inside pipe over the entire length;

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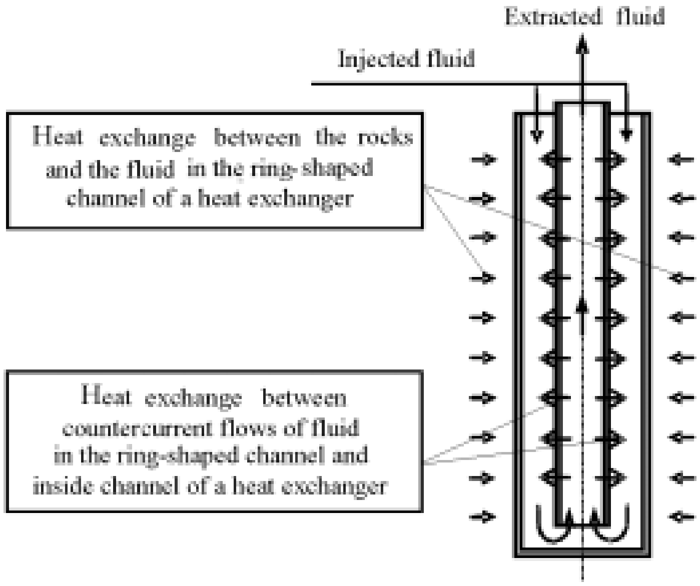

Fig. 1. The scheme of fluid flow and heat exchange in a double-pipe exchanger.

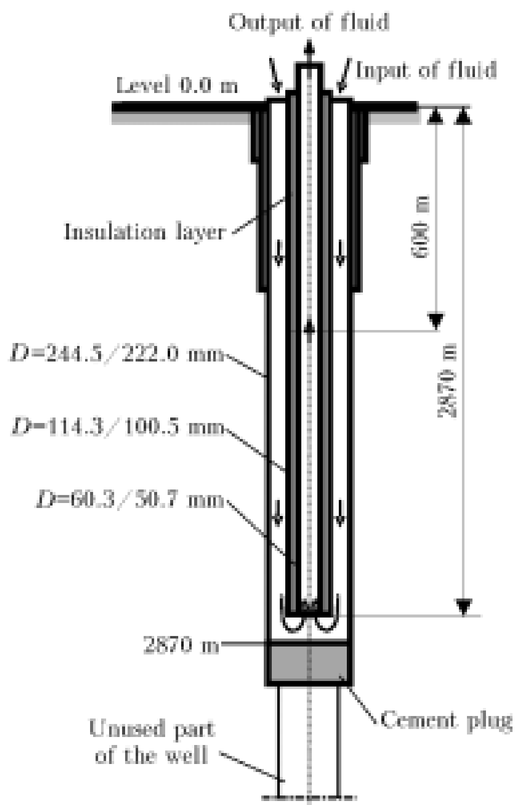

Fig. 2. The scheme of a geothermal heat exchanger in the Jachówka K-2 well at the depth L = 2870 m [1].

* air-gap insulation formed by the casing of steel pipes of diameters 114.3/100.5 mm with the total length equal to the length of the inside column of the exchanger put on the inside column of pipes of diameter 60.3 mm;

* insulation of the polyurethane foam put on the organic top part of the inside column of pipes of diameters 114.3/60.3 mm and a total length of 600 m.

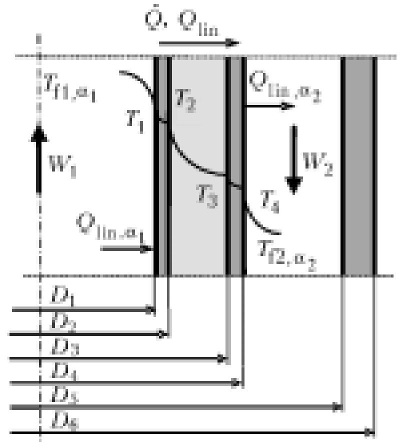

Fig. 3. The scheme of a cylindrical barrier and the thermal field.

2. Thermophysical Parameters of the Center Surrounding the Injection-Production Well. To make model calculations, which are essential for estimation of the amount of heat that can be gained in the Jachówka K-2 well, the selected thermophysical parameters of geological strata surrounding the well must be known. The well allowed a geological analysis over the entire depth, and it was possible to work out a geological profile of the surrounding of the well.

Parameters such as the depth of strata, their volume thickness, the heat-transfer coefficient, and temperatures as well as the distributions of temperature and pressure are taken from the data obtained from Polgeotermia. Because of a nonuniform depth of strata, mean values of the given thermophysical parameters are determined as weighted means. The thickness fraction of the given stratum in the total thickness was the deciding factor. The fraction of depth and the thickness of strata relate to the apparent values measured by plumb.

According to the computational model of heat exchange in vertical probes, a linear distribution of orogenic temperatures was assumed. The function describing the distribution of temperatures was determined by extrapolation of the results obtained:

$$T(H) = 7.03 + 0.025H\,, \tag{1}$$

where H is the length of the heat exchanger. The other essential parameters were taken from the available literature [2].

3. The Coefficient of Heat Transfer through the Cylindrical Barrier. In analysis of heat exchange between two countercurrent fluids flowing in a double-pipe heat exchanger, the processes that accompany the exchange should be considered. The fluid of higher temperature flows up in the inside pipe, which is washed by the countercurrent fluid of lower temperature flowing in the outside ring-shaped channel. Heat penetration on washed surfaces and heat conduction through the barrier separating the two fluxes accompany the motion of fluids. The separating wall may be a multilayer barrier, which results from the conception of the heat-exchanger construction (Fig. 3).

On the assumption of a steady state and additionally a constant fluid temperature, the following condition must be satisfied: the heat flux penetrating from the first fluid is equal to the heat flux conducted through the multi-layer cylindrical barrier, which in turn is equal to the heat flux penetrating into the other fluid. The linear density of the heat flux transferring from one medium into the other is determined from the following relation:

$$Q_{\text{lin}} = \pi k_{\text{lin}} (T_{\text{f1}} - T_{\text{f2}}) = \frac{\pi (T_{\text{f1}} - T_{\text{f2}})}{R_{k_{\text{lin}}}}\,, \tag{2}$$

where

$$\frac{1}{k_{\text{lin}}} = \frac{1}{\alpha_1 D_1} + \sum_{i=1}^{n} \frac{1}{2\lambda_i} \ln \frac{D_{i+1}}{D_i} + \frac{1}{\alpha_2 D_{n+1}}\,, \tag{3}$$

$$R_{k_{\mathrm{lin}}} = R_{\mathrm{lin},\alpha_1} + \sum_{i=1}^{n} R_{\mathrm{lin},\lambda_i} + R_{\mathrm{lin},\alpha_2} \,. \tag{4}$$

Using the definition of linear density of a heat flux $Q_{\mathrm{lin}} = \dot{Q}/l$, we obtain from relation (2)

$$\dot{Q} = k_{\mathrm{w}} A_0 \,(T_{\mathrm{f1}} - T_{\mathrm{f2}}) = k_{\mathrm{w}} A_0 \Delta T \,, \tag{5}$$

$$\frac{1}{k_{\mathrm{w}}} = D_0 \frac{1}{k_{\mathrm{lin}}} = D_0 \left(\frac{1}{\alpha_1 D_1} + \sum_{i=1}^{n} \frac{1}{2\lambda_i} \ln \frac{D_{i+1}}{D_i} + \frac{1}{\alpha_2 D_{n+1}} \right). \tag{6}$$

Relation (5) is valid if T_{f1} and T_{f2} are constant or taken to be mean temperatures. The coefficients of convective heat transfer in relation (6) can be determined based on the dimensionless equations from [3]. The Nusselt number is related to the coefficient of convective heat transfer α by the following equation:

$$\overline{\alpha} = \frac{\lambda}{l} \overline{\mathrm{Nu}} \,. \tag{7}$$

To determine the coefficient of convective heat transfer in the turbulent fluid flow in the inside channel of the Field exchanger, Mikheev's equation, which holds within the range Re = 10^4–$5{\cdot}10^6$ and Pr = 0.6–2500, can be used:

$$\mathrm{Nu} = 0.021\, \mathrm{Re}_{\mathrm{f}}^{0.8}\, \mathrm{Pr}_{\mathrm{f}}^{0.43} \left(\frac{\mathrm{Pr}_{\mathrm{f}}}{\mathrm{Pr}_{\mathrm{w}}} \right)^{0.25} . \tag{8}$$

To determine the coefficient of convective heat transfer in the fluid flow in a ring-shaped channel, we must use two equations, adjusted to the character of fluid flow in the channel. For the laminar flow the Nusselt number can be determined from Sarma's relation

$$\mathrm{Nu} = 0.155 \left(1 - \frac{D_{\mathrm{w}}}{D_{\mathrm{z}}} \right)^{2/3} \mathrm{Re}_{\mathrm{f}}^{0.645}\, \mathrm{Pr}_{\mathrm{f}}^{1/3} \left(\frac{\eta_{\mathrm{f}}}{\eta_{\mathrm{w}}} \right)^{0.14} , \tag{9}$$

which is valid within the range Re = 10^3–$1.5{\cdot}10^4$, whereas for turbulent flow, from Averin's equation we have

$$\mathrm{Nu} = 0.021\, \mathrm{Re}_{\mathrm{f}}^{0.8}\, \mathrm{Pr}_{\mathrm{f}}^{0.43} \left(\frac{\mathrm{Pr}_{\mathrm{f}}}{\mathrm{Pr}_{\mathrm{w}}} \right)^{0.25} . \tag{10}$$

This dependency holds within the range Re = $6{\cdot}10^3$–$4{\cdot}10^5$. Equations (9) and (10) relate to two-sided heat penetration to both the inside and the outside surface of the ring-shaped channel.

4. The Overall Coefficient of Heat Exchange between a Deposit and Fluid. To determine the thermal field for unsteady heat transfer from the surrounding rock deposit, it is possible to use the known solution of the heat-transfer equation with the given boundary conditions. Some of the solutions, considering the mean thermophysical parameters of the rock deposit, allow one to determine the time-dependent linear thermal resistance in the rock deposit.

In [4, 5], the method of calculation of the linear thermal resistance of the rock deposit is given. The method uses a time-dependent radius of interaction of the center $r_{\mathrm{s}} = f(t)$ in heat conduction in the rock deposit. According to [6, 7], if $r_{\mathrm{s}} >> r_{\mathrm{w}}$, the radius r_{s} increasing with time can be determined from the following relation:

$$r_{\mathrm{s}} = 2 \sqrt{a_{\mathrm{s}} t} \,, \tag{11}$$

where r_{w} is the radius of a hole in the rock. Then the linear thermal resistance in the rock deposit is obtained from the equation

$$R_s = \frac{1}{2\lambda_s} \ln \frac{2\sqrt{a_s t}}{r_w} . \tag{12}$$

The total thermal resistance for heat conduction from the fluid into the rock deposit is determined as

$$R_t = R_\alpha + \sum_{i=1}^{n} R_{\lambda_i} + R_s = \frac{1}{2r_1\alpha} + \frac{1}{2} \sum_{i=1}^{n} \frac{1}{\lambda_i} \ln \frac{r_{i+1}}{r_i} + \frac{1}{2\lambda_s} \ln \frac{2\sqrt{a_s t}}{r_{n+1}} . \tag{13}$$

For deep wells, the resistance of the casing can be ignored and the linear thermal resistance is determined from the following relation:

$$R_t \cong \frac{1}{2r_1\alpha} + \frac{1}{2\lambda_s} \ln \frac{2\sqrt{a_s t}}{r_{n+1}} . \tag{14}$$

The linear density of the heat flux is

$$Q_{lin} = \frac{\pi \Delta \overline{T}}{R_t} = \pi k_{lin} \Delta \overline{T} \tag{15}$$

and the density of the transferred heat flux is described by relation

$$\dot{Q} = k_z A_1 \Delta \overline{T} = k_z \pi D_1 l \Delta \overline{T} = k_z \pi D_1 l \, (\overline{T}_s - \overline{T}_f) , \tag{16}$$

where $\overline{T}_s$ is the mean temperature of the rock at a considerable distance from the hole and $\overline{T}_f$ is the mean fluid temperature.

According to Charnyi [6, 7], the overall heat-transfer coefficient k_z may be determined from the following equations:

$$\frac{1}{k_z} = 2r_1 \frac{1}{k_{lin}} = D_1 \frac{1}{k_{lin}} = D_1 R_t = \frac{1}{\alpha} + \frac{D_1}{2} \sum_{i=1}^{n} \frac{1}{\lambda_i} \ln \frac{D_{i+1}}{D_i} + \frac{D_1}{2\lambda_s} \ln \frac{4\sqrt{a_s t}}{D_{n+1}} \tag{17}$$

or

$$\frac{1}{k_z} \cong \frac{1}{\alpha} + \frac{D_1}{2\lambda_s} \ln \frac{4\sqrt{a_s t}}{D_1} . \tag{18}$$

Another method of determination of the heat-transfer coefficient is given by Dyad'kin and Gendler [8]. Based on the analytical solutions presented in [9–11], they recommend the following equation:

$$k_z = \frac{k_z'}{1 + \mathrm{Bi} \ln (1 + \sqrt{\overline{\gamma}\mathrm{Fo}})} , \tag{19}$$

where

$$\frac{1}{k_z'} = \frac{1}{\alpha} + \frac{D_1}{2} \sum_{i=1}^{n} \frac{1}{\lambda_i} \ln \frac{D_{i+1}}{D_i} , \tag{20}$$

$\mathrm{Bi} = \frac{\alpha r_1}{\lambda_s}$ is the Biot number, $\mathrm{Fo} = \frac{a_s t}{r_1^2}$ is the Fourier number, and $\overline{\gamma}$ is the parameter depending on the Biot number. If $\mathrm{Bi} \to \infty$, which actually means that $\mathrm{Bi} > 30$, $\overline{\gamma} = \pi$; in the other cases, $\overline{\gamma} = 2$. If $\mathrm{Bi} > 30$, relation (19) can be written as follows:

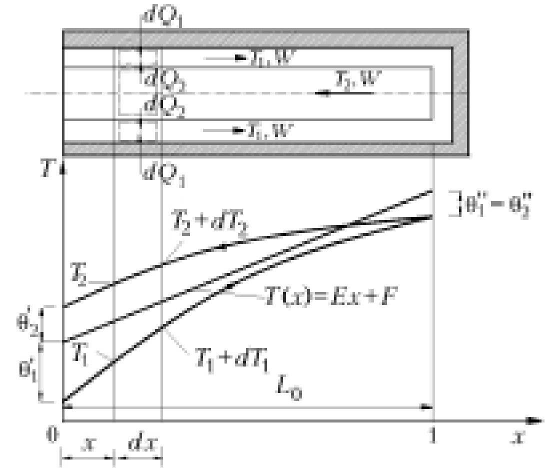

Fig. 4. The thermal field of a heat carrier in the heat exchanger at a temperature of the injected fluid which is lower than the temperature of the deposit on the surface.

$$k_z = \frac{k_z'}{1 + \text{Bi}\ln(1+\sqrt{\pi\text{Fo}})} . \tag{21}$$

If $\text{Bi} \to \infty$, (19) results in

$$k_z \cong \frac{\lambda_s}{r_1 \ln(1+\sqrt{\pi\text{Fo}})} . \tag{22}$$

According to the model describing heat transfer in the geothermal heat exchanger, relation (16) was used in the differential form:

$$d\dot{Q} = k_w (T_s - T_1)\, dA . \tag{23}$$

For the selected thermophysical parameters of the rocks and the geothermal heat exchanger, the overall heat-transfer coefficient as a function of time was calculated using the equations developed and recommended by Dyad'kin and Gendler [8] and Charnyi [6, 7]. The values of k_z are close to each other, and in time more than 100 h they do not change substantially. Thus, it is suggested that Charnyi's equation be used in the calculations.

5. A Computational Model of the Vertical Heat Exchanger at a Variable Temperature of the Deposit. The circulating fluid injected into the ring-shaped channel of the Field heat exchanger flows down to the lower part of the exchanger. At the lower dead center the fluid reaches the maximum temperature, which depends on, among other things, the heat-exchange conditions and the flow rate. Then it flows up to the surface of the earth through the inside channel.

On the outside wall of the ring-shaped channel, heat exchange between the rock layers and the injected fluid occurs. If the temperature of water at the input is lower than the temperature of the deposit on the surface, heat is transferred from the rock to the water [12, 13]. However, if the injected fluid has a higher input temperature than the deposit temperature on the surface of the given part of the exchanger, heat exchange occurs in the opposite direction, i.e., from the fluid to the rocks. In both cases, it is assumed that the temperature of the deposit changes linearly with the exchanger depth.

Heat exchange also takes place on the inside wall of the channel, which is a barrier between two countercurrent flows of the circulating fluid. The heated fluid flowing up through the inside pipe conducts a part of the heat to the colder water flowing down through the outside ring-shaped channel. As a result, the temperature of fluid flowing out at the surface decreases relative to the temperature at the dead center. In the special case where the inside pipe is perfectly insulated, heat exchange between the flows of fluid does not occur.

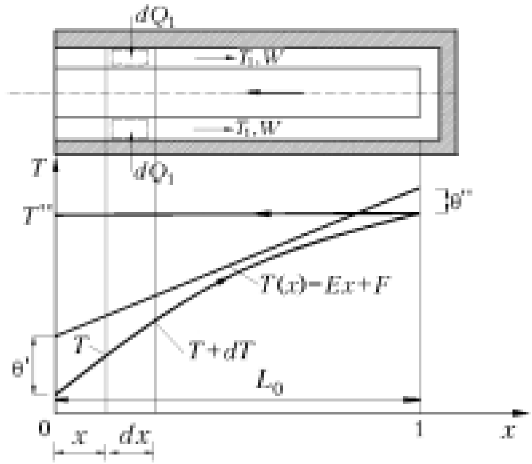

Fig. 5. The thermal field of a heat carrier in the heat exchanger with the perfect inside insulation at a temperature of the injected fluid which is lower than the temperature of the deposit on the surface.

Figure 4 presents the scheme of the heat exchanger and the basic thermal fields of a heat carrier assuming heat exchange between the fluids injected through the ring-shaped channel and extracted through the inside pipe. Figure 5 shows the thermal field of a heat carrier when the inside pipe is perfectly insulated.

6. Results of Calculations of the Geothermal Heat That Can Be Aquired in the Jachówka K-2 Well. All the computational approaches for the Field heat exchanger were worked out on the basis of the method presented in Secs. 2–4 and in [1]. The calculations were performed for selected volume flow rates of water flowing through the heat exchanger, namely, for $\dot{V}$ = 2, 10, 20, and 30 m^3/h. The temperature of the injected water was equal to T_1' = 10, 15, 20, and 25^oC. The temperature of the stratum at a depth of 2870 m reached 78.78^oC and it was equal to 7.03^oC at the ground level.

The final results of the calculations related to different types of insulation of the inside channel of the Field heat exchanger are shown in Table 1. The table includes the following quantities: temperature of the fluid at the output of the geothermal heat exchanger as a function of flow rate and temperature of the injected circulating fluid, as well as the corresponding values of heat power and amount of heat that can be acuired in a year.

CONCLUSIONS

To assess the theoretical possibilities of acquiring geothermal heat at a depth of 2870 m, the calculations were carried out on the assumption that the inside pipe of the exchanger is perfectly insulated. The results of the calculations demonstrate the practical significance of the existing hole for two water flow rates: $\dot{V}$ = 2 and 10 m^3/h. It is possible to determine the temperature at the output of the heat exchanger and the value of the gained heat power for both cases.

Considering the hole with an air gap over the whole depth and a temperature of water at the input of the heat exchanger of 25^oC, we obtain the following:

* for $\dot{V}$ = 2 m^3/h, the water temperature at the output is about 65^oC and the gained heat power is equal to $\dot{Q} \cong 91$ kW. This gives Q = 770 MWh = 2760 GJ of geothermal heat gained in a year;

* for $\dot{V}$ = 10 m^3/h, the water temperature at the output is about 47^oC and the gained heat power is equal to $\dot{Q} \cong 255$ kW. This gives Q = 2150 MWh = 7730 GJ of geothermal heat gained in a year.

In almost all of the cases considered, utilization of geothermal heat at lower temperatures of the surrounding requires the top boiler to be used in order to reach the required temperature of water in a heat-distribution network in the feeding. In other cases, with the inside pipe insulated over the whole length, for larger volume flow rates of water the effects are smaller, even though it is possible to gain relatively large heat fluxes. However, the temperatures are substantially lower.

TABLE 1. Results of the Calculations for the Heat Exchanger of Length L = 2870 m with Different Types of Inside-Pipe Insulation

No.	$\dot{V}$, m^3/h	T_1, ^{o}C	Perfect insulation			Air gap			Polyurethane foam		
			T_2, ^{o}C	$\dot{Q}$, kW	Q, MWh/a	T_2, ^{o}C	$\dot{Q}$, kW	Q, MWh/a	T_2, ^{o}C	$\dot{Q}$, kW	Q, MWh/a
1	2	10	69.98	138.03	1163	64.42	124.68	1050	20.01	22.98	194
2	2	15	70.01	126.48	1065	64.53	113.35	955	20.57	12.77	108
3	2	20	70.03	114.92	968	64.65	102.17	861	21.08	2.48	21
4	2	25	70.04	103.39	871	64.76	90.91	766	21.64	–7.72	–65
5	10	10	44.68	400.97	3378	44.23	394.68	3325	17.39	84.96	716
6	10	15	45.63	353.73	2980	45.21	347.93	2931	19.98	57.28	483
7	10	20	46.56	306.54	2582	46.18	301.24	2538	22.63	30.20	254
8	10	25	47.53	259.51	2186	47.16	254.78	2146	25.24	2.70	23
9	20	10	31.67	502.53	4233	31.61	499.76	4210	16.72	154.76	1304
10	20	15	33.86	436.41	3676	33.79	434.03	3656	20.01	115.19	970
11	20	20	36.01	370.08	3118	35.94	367.97	3100	23.29	75.74	638
12	20	25	38.16	303.75	2559	38.10	301.95	2544	26.63	37.37	315
13	30	10	25.68	546.06	4600	25.68	545.04	4591	16.27	216.79	1826
14	30	15	28.55	471.05	3968	28.53	469.81	3958	19.87	168.19	1416
15	30	20	31.40	395.70	3333	31.39	394.57	3324	23.48	120.23	1013
16	30	25	34.25	320.37	2699	34.23	319.44	2691	27.11	72.93	614

The amount of geothermal heat gained is connected with the temperature of the water injected into the heat exchanger. The water temperature in the calculations was assumed to be 25^{o}C. When the temperature decreases, both the heat power of a geothermal intake and the amount of gained energy increase. However, an increase in the temperature worsens the exploitation parameters, thus giving a smaller heat power, and the amount of gained energy decreases. Hence, it is important to use the well in such a way that the maximum heat from the circulating water and the maximally lower return temperature be reached.

The conclusions are formulated with respect to the heat flux used for heating. They should be drawn in another way if there is any possibility of using the heat flux for other purposes than heating when the water temperature at the output from the hole is lower.

The proposed heat exchanger with insulation along a length of 600 m does not lead to expected effects due to the low temperature of the flowing-out water.

NOTATION

A_0, surface of heat transfer, m^2; a, thermal diffusivity of a rock deposit, m^2/sec; Bi, Biot number; c, specific heat at constant pressure, J/(kg·K); D, diameter, m; D_0, equivalent diameter, m; D_z, inner diameter of the outside pipe, m; D_j (j = 1, 2, 3, ..., 6), diameter, see Fig. 3, m; Fo, Fourier number; H, length of the heat exchanger, m; k, heat-transfer coefficient, W/(m^2·K); k_{lin}, linear heat-transfer coefficient, W/(m·K); L, depth of the heat exchanger, m; L_0, length of the inside pipe, m; l, length, m; Nu, Nusselt number; Pr, Prandtl number; Re, Reynolds number; Q, geothermal heat, GJ; Q_{lin}, linear density of heat flux, W/m; $\dot{Q}$, heat power, W; R, thermal resistance, m·K/W; r, radius, m; t, time, sec; T, temperature, ^{o}C; $\dot{V}$, volume flow rate, m^3/h; W, heat capacity, J/K; x, coordinate, m; α, convective heat-transfer coefficient, W/(m^2·K); $\bar{\gamma}$, dimensionless parameter; $\vartheta_1' = T_x - T_1$ at x = 0, temperature difference, ^{o}C; $\vartheta_2' = T_2 - T_x$ at x = 0, temperature difference, ^{o}C; λ, thermal conductivity, W/(m·K); ρ, density, kg/m^3. Subscripts: f, fluid; lin, linear; s, rock; t, total; w, wall; 1 and 2, first (in the ring-shaped channel) and second (in the inside conductor of the heat exchanger) fluids.

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