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Flow Rate Estimate from Distinct Geothermal Aquifers Using Borehole Temperature Logs

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The article describes the procedure of flow rate estimation from distinct geothermal aquifers using borehole temperature logs at static and dynamic conditions. For this purpose, a mathematic and computer programme was developed. Borehole temperature logs give useful information on location and amount of geothermal water from distinct geothermal aquifers. In this way, accurate data on permeability and water bearing of separate geothermal aquifers can be obtained.

Ocjenjivanje protoka pojedinačnih slojeva u geotermalnoj bušotini pomoću temperaturne karotaže

Izvornoznanstveni članak

Članak daje prikaz postupka ocjenjivanja protoka pojedinačnih slojeva u geotermalnoj bušotini pomoću temperaturne karotaže u statičkim i dinamičnim uvjetima. U tu svrhu razvili smo matematički model i kompjutorski program. Temperaturna karotaža može dati korisne podatke o lokaciji i količini protoka geotermalne vode iz pojedinačnih slojeva u bošotinu. Na taj način možemo odrediti precizne podatke o propustnosti i protoku pojedinačnih slojeva.

1. Introduction

Geothermal energy is the heat contained within the Earth, which can or could be recovered and exploited by humankind [1]. Geothermal energy of the Earth represents a great potential, yet until now the use of this kind of energy has been limited to areas where the geological structure enables the holder of heat (water in liquid state or steam) to carry it from the deeper, hotter layers to the surface [2]. The use of geothermal energy has been most efficient in areas where it is closer to the Earth's crust, which is on geothermal faults and at volcanic areas [3].

Slovenia lies in the convergent area of the African and Eurasian tectonic plates. More information on geological aspects can be found in [4] and [5]. The total direct use of geothermal energy in Slovenia amounted in 2004 to about 673 TJ at 27 locations [6].

North-eastern Slovenia is a transitional region between the Pannonian lowland in the east and Southern Alps in the west. The most important tectonic structure is the Mura basin, which is is filled with clastic sediments of the Tertiary and Quarternary age. The Mura basin forms a part of a much larger Zala basin, which extends from south-western Hungary to northern Croatia and belongs to a widespread system of Pannonian basins [7].

Flow rate estimate from a distinct geothermal aquifer based on borehole temperature logs and DLL/GR (DualLateroLog and Gamma Ray) before run the casing, has been carried out in a geothermal well in North-eastern Slovenia up to 1583,28 meters depth. The producing aquifer is composed of several water bearing sandy layers, interbedded with silts and clays, up to 60 m thick.

Symbols/Oznake

- c_p - specific heat capacity, J/kg·K
  - specifični toplinski kapacitet
- N - number of layers
  - broj slojeva
- q_v - volumetric flow, m³/s
  - volumni protok
- T - temperature, K
  - temperatura
- ϑ - temperature, ºC
  - temperatura
- ρ - density, kg/m³
  - gustoća
- Φ_o - heat flow of the geothermal water at outflow from the measured layer, W
  - toplinski tok geotermalne vode mjernog sloja na istjecanju
- Φ_i - heat flow of the geothermal water at inflow to the measured layer, W
  - toplinski tok geotermalne vode mjernog sloja na dotoku
- Φ_s - heat flow of the goethermal water measured at a static temperature, W
  - toplinski tok geotermalne vode pri statičkoj temperaturi

Indices/ indeksi

- i - inflow
  - dotok
- o - outflow
  - istjecanje
- j - j-th layer
  - j-ti sloj

The research comprised the development of a mathematical model, based on which a computer programme for calculation of flow rate estimate for geologic layers was developed. Input data for the computer programme are the results of the measurements at various depths at static and dynamic conditions.

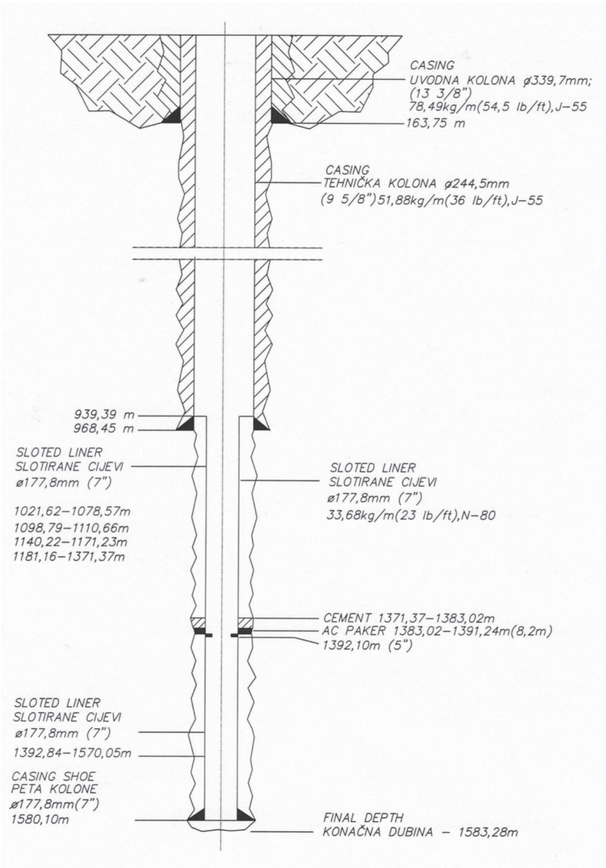

Figure 1. Technical state of a geothermal well

Slika 1. Tehničko stanje u bušotini

The geothermal well, with the technical state as shown on the Figure 1, was drilled to a depth of 1583,28 meters.

2. Borehole temperature logs

Even though measuring the temperature in a well is simple and precise, it is often neglected in practice as a suitable tool for qualitative and quantitative flow rate estimate of separate aquifers in a geothermal well. Optimum data for any geothermal investigation are densely sampled, high precision temperature logs from boreholes. They should represent the formation temperature as accurately as possible [8].

Movement of water in a borehole is detectable by precise and repeated temperature measurement [9]. Temperature patterns in a borehole may be interpreted to reveal very small water flows [10]. For interpretation of borehole temperature logs [11] it is necessary to know all the factors that affect the temperature in a borehole [12]. The factors include the temperature of separate layers, heat transmission between the borehole and separate layers, convection of heat due to flow of fluids and thermal changes of fluids in dynamic conditions [13] – figure 2.

In order to make a qualitative and quantitative interpretation of the flow from separate layers geothermal gradient needs to be determined in static conditions (borehole shut in) and in dynamic conditions (water flows out of the borehole).

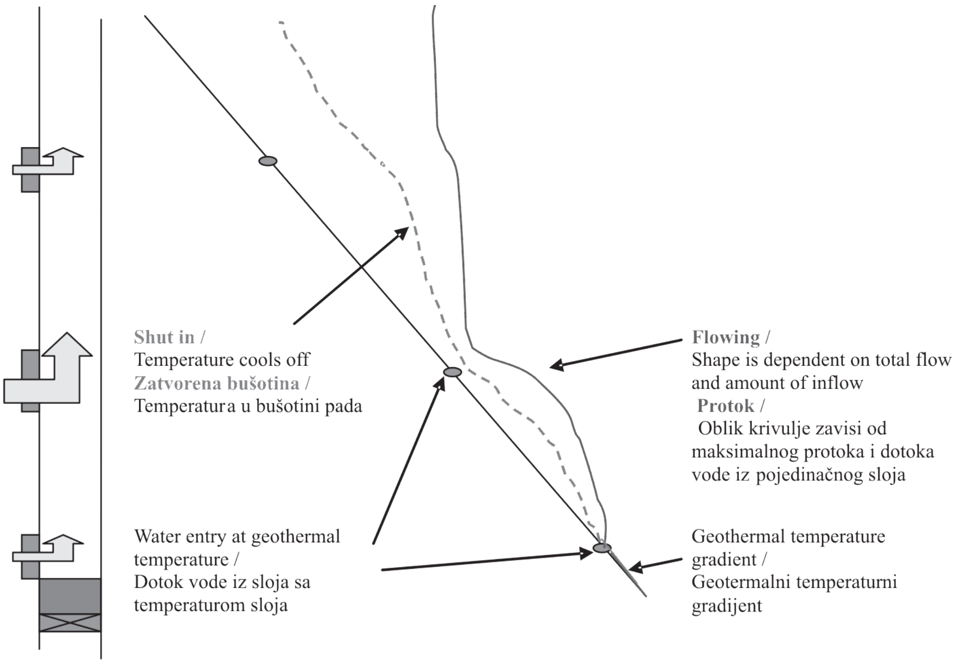

Figure 2. Temperature profile in a borehole
Slika 2. Temperaturni profil bušotine

Due to the changes in composition of separate layers of the borehole, the temperature profile is varied, so that the inclination of the curve denoting changes of temperature with depth (geothermal gradient) varies according to the formation.

The geothermal gradient depends on thermal conductivity of separate layers. The higher the thermal conductivity, the easier heat is transmitted through the rock. The geothermal gradient is the basis for interpretation of borehole log temperature. If geothermal water in separate layers is still, the geothermal gradient will increase constantly with depth. If geothermal water flows, the change in temperature is shown at the inflow of water into the well. Changes in temperature with depth are represented by the dynamic temperature gradient. Dynamic temperature at a certain depth therefore differs from the temperature measured under static conditions [14].

If the flow of geothermal water in the borehole stops, the temperature in the well starts falling, until it reaches the temperature of separate layers of rocks in the depth. This process is an appropriate basis for a qualitative and quantitative interpretation.

Familiarity with the course of temperature in a well is crucial for estimation of geothermal resources and reserves as well as for defining the mechanism of dynamics of fluids. Borehole temperature can be determined in different ways:

- by continuous measurement of temperature in the well in dependence of the depth (borehole temperature logs) at this it is very important for the well to be in a temperature balance and that the temperature is not under the influence of various procedures of drilling any more (drilling, rinsing, cementing),
- by measuring the temperature at the end of drilling (BHT – bottom hole temperature)
- by measuring the outflow temperatures of water.

Borehole temperature logs give useful information on location and amount of geothermal water from separate geological layers in the well. In this way, accurate data on permeability and water bearing of separate layers can be obtained.

Based on data by borehole temperature logs, a new geothermal well in nearby surroundings can be drilled only to the most productive geological layer.

The advantages of determining the productivity of separate geological layers using borehole temperature logs are:

- simplicity of the performed measurements,
- relatively low costs of the measurements and
- possibility to measure in various technological and technical circumstances (free flow wells, case hole and wells that are hydro dynamically connected with multiple beds).

The disadvantages of determining the productivity of separate geological layers using borehole temperature logs are:

- inaccurate data in case of a gas discharge in the well
- difficult interpretation when the well has low productivity

- difficult interpretation when the well has more productive beds with similar temperature.

Flow rate estimate of layers of geothermal water is one of the basic data needed to determine:
- hydro geological properties of the productive layer (transmissivity, permeability, coefficient of storage, form and size of the draining area),
- energetic characteristics of the geothermal system (energy potential, calorific power of the system).

If there is no inflow or outflow of geothermal water in the well (stationary state), the temperature in the well increases gradually with depth as a function of geothermal temperature gradient.

The measurement of temperature in the well serves two purposes:
- detection of temperature anomalies in the well,
- quantitative determination of heat output in the well.

Temperature anomalies in the well point to a presence of geothermal activity. Thermal conductivity of rock [15] is determined in a laboratory on samples of rocks, whereas the temperature is measured inside the well.

Determination of the temperature inside the well is not as simple as it may seem. In wells that are drilled with bentonite mud, it happens that during drilling, the circulation of the mud causes a change in the temperature of the rocks. In order to establish a stationary state, the waiting period needs to be longer than the drilling period. Fortunately there are various methods with which stabilization of temperature in the well can be predetermined.

One of the methods is based on the measurement of temperature in the well at various depths in fixed time intervals after the drilling is finished.

2.1. Results of the measurements

Figure 3 shows the results of the measurements of static and dynamic temperature in a geothermal borehole.

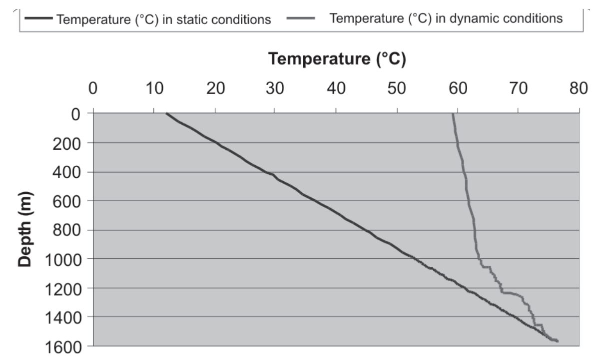

Figure 3. Water temperature at static and dynamic conditions in depths from 0 to 1600 m.

Slika 3. Temperatura vode u bušotini u statičkim i dinamičnim uvjetima od 0 do 1600 m

Measurements of temperature at static (q_v=0 l/s) and dynamic conditions (q_v=15 l/s) have been carried out to 950 m depth at every 50 meters, and from 980 m to 1575 m at every 5 meter depth.

3. Mathematic model

Hydrodynamic and thermodynamic processes going on during the exploitation of a geothermal borehole and rocks from the bottom to the top are quite complex for an exact analytic integration of a system of differential equations that describe the process. Therefore the mathematical model is based on a simplified presumption which considers the stationary flow without environmental disturbances and temperature loss, so we can define volume flows of separate layers based on the measured temperatures at static and dynamic conditions at various depths. The basis of the equation is heat balance of separate measured layers:

$$\Phi_0 = \Phi_i + \Phi_S. \tag{1}$$

Heat flow is determined with the equation:

$$\Phi = \sum_{j=1}^{N} c_{p,j} \cdot q_{m,j} \cdot \Delta T_j = \sum_{j=1}^{N} c_{p,j} \cdot q_{v,j} \cdot \rho_j \cdot \Delta T_j \,. \tag{2}$$

Volumetric flow of inflow from j+1 layer into j layer is:

$$q_{v,i,j} = q_{v,o,j} - q_{v,j}. \tag{3}$$

Based on figure 4, showing j-th layer with noted static and dynamic temperatures and volumetric flows, provided c_p and ρ in j-th layer are constant and bearing in mind equations (1) and (2), we can say:

$$q_{v,o,j} \cdot T_{o,j} = q_{v,i,j} \cdot T_{i,j} + q_{v,j} \cdot \overline{T}_{s,j} \,. \tag{4}$$

Temperature measured at dynamic conditions is without index “s”.

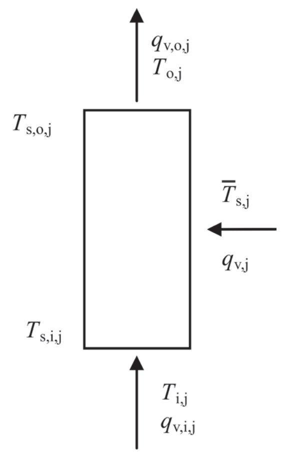

Figure 4. Flow chart of a layer with inserted sloted liner, with marked static and dynamic temperatures and volumetric flows

Slika 4. Shematski prikaz sloja sa slotiranim cijevima, statičkim i dinamičnim temperaturama i volumskim protocima

It follows that:

$$\overline{T}_{\mathrm{s,j}} = \frac{T_{\mathrm{s,o,j}} + T_{\mathrm{s,i,j}}}{2} \,. \tag{5}$$

With readjustment of the equation (4) as follows:

$$q_{\mathrm{v,o,j}} \cdot T_{\mathrm{o,j}} = \left(q_{\mathrm{v,o,j}} - q_{\mathrm{v,j}}\right) \cdot T_{\mathrm{i,j}} + q_{\mathrm{v,j}} \cdot \overline{T}_{\mathrm{s,j}} \,. \tag{6}$$

Volumetric flow of j-th layer through perforation of slotted liner $q_{\mathrm{v,j}}$ (Figure 4) is obtained by readjustment of the equation (6):

$$q_{\mathrm{v,j}} = q_{\mathrm{v,o,j}} \cdot \frac{T_{\mathrm{o,j}} - T_{\mathrm{i,j}}}{\overline{T}_{\mathrm{s,j}} - T_{\mathrm{i,j}}} \,. \tag{7}$$

In order for energy balance with borehole temperature logs of the measured layer to be correct - equation (6) or (7), the following conditions have to apply:

$$T_{\mathrm{o,j}} < T_{\mathrm{i,j}} \;\; \text{in} \;\; \overline{T}_{\mathrm{s,j}} < T_{\mathrm{i,j}} \,. \tag{8}$$

The computer programme GEOFLOW version V1.2 is based on the presented mathematical model.

4. Conversion results for productivity of geological layers with the computer programme GEOFLOW V1.2

The conversion results for flow rate estimate of geologic layers with computer programme GEOFLOW V1.2 are shown in Table 1. By reason of scale, Table 1 only shows a part of the results.

Table 1. Conversion results for productivity of geological layers with the computer programme GEOFLOW V1.2

Tablica 1. Rezultati izdašnosti geoloških slojeva dobijenih kompjutorskim programom GEOFLOW V1.2

Layer	from, m	t_o, m	q_{vs}, l/s	q_v, l/s	%	ϑ_s, °C	ϑ_i, °C	ϑ_o, °C
s 29	1025	1020	15.000	0.000	0.00	51.01	63.88	63.88
s 30	1030	1025	14.871	0.129	0.86	51.01	63.99	63.88
s 31	1035	1030	14.847	0.024	0.16	51.40	64.01	63.99
s 32	1040	1035	14.776	0.071	0.48	51.59	64.07	64.01
s 33	1045	1040	14.716	0.060	0.40	51.78	64.12	64.07
s 34	1050	1045	14.123	0.593	3.96	51.98	64.63	64.12
s 35	1055	1050	13.641	0.482	3.21	52.18	65.07	64.63
s 36	1060	1055	13.587	0.053	0.36	52.37	65.12	65.12
s 37	1065	1060	13.469	0.118	0.79	52.57	65.23	65.12
s 38	1070	1065	13.246	0.223	1.49	52.77	65.44	65.23
Productivity of the well is 15.0 l/s								

Sign "s" means sloted liner.

Based on the data from measurements of the temperature gradient at static and dynamic conditions and calculations with the computer programme GEOFLOW V1.2 (Table 1), the results of the calculations for the inflow of water into the well is shown in Figures 5, 6 and 7.

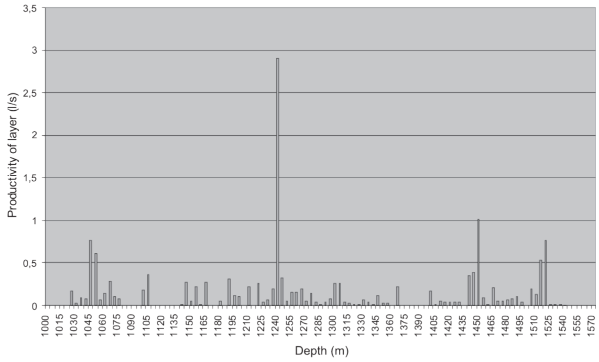

Figure 5. Productivity of separate layers (l/s) at joint flow q_v=15 l/s of geothermal water

Slika 5. Protok pojedinačnih slojeva (l/s) kod masimalnog protoka (15 l/s) geotermalne vode

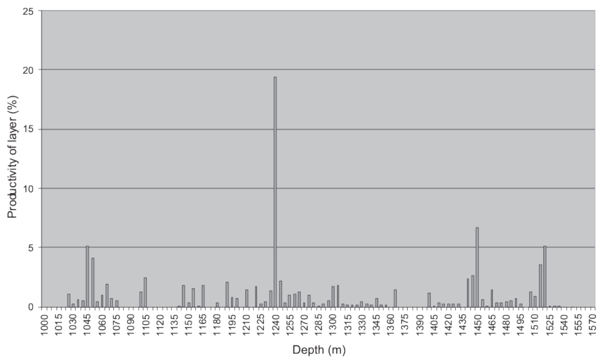

Figure 6. Productivity of separate layers (%) at joint flow q_v=15 l/s of geothermal water

Slika 6. Protok pojedinačnih slojeva (%) kod masimalnog protoka (15 l/s) geotermalne vode

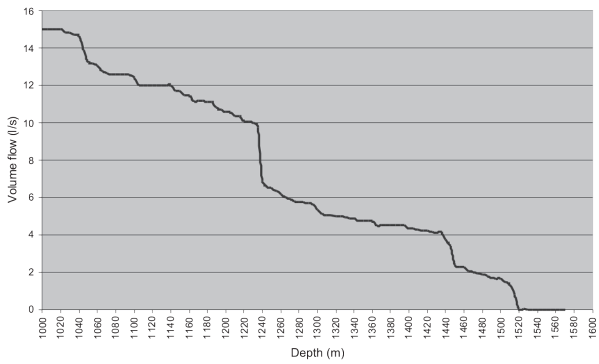

Figure 7. Total volumetric flow rate (l/s) in the well depending on the depth

Slika 7. Cjelokupni volumni protok (l/s) u bušotini u ovisnosti o dubini

5. Conclusion

Flow rate estimate of separate geological layers in a geothermal well can be qualitatively and quantitatively defined on the basis of well log temperature (measurement of temperature depending on the depth) in static and dynamic conditions.

Where fluid comes into the well, temperature anomalies can be observed, which serve for a qualitative determination of inflow of geothermal water from separate layers. The qualitative determination of separate layer productivity carried out, based on borehole temperature logs, is in total agreement with the interpretation of well log measurements DLL and GR.

The results of the given mathematical model and computer programme GEOFLOW V1.2 are dependent on measured temperatures at static and dynamic conditions at various depths and energy balance of each by means of well log temperature from the measured geological layer.

Productivity of separate layers in a geothermal well has been verified with a flow meter. The results of the measurements matched the results obtained with the computer programme GEOFLOW V1.2 based on the data from borehole temperature logs.

The advantage of temperature measurement in static and dynamic conditions and the GEOFLOW V1.2 computer programme calculation is in the fact that the flow rate estimate of separate layers in a geothermal well can be established quickly and with low costs.

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