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HEAT TRANSFER IN A LOW ENTHALPY GEOTHERMAL WELL

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ABSTRACT

The well from the University of Oradea campus is a typical low enthalpy geothermal well with multiple feed zones, about 3,000 m deep, 80÷85°C well head temperature, and about 30 l/s maximum artesian flow rate. This well was used to study the heat transfer between the geothermal fluid and the surrounding rock during artesian production.

The hydrodynamic and thermodynamic processes that occur during exploitation in the well and surrounding rock, from bottom to surface, are too complex for an exact analytical integration of the differential equations system. An analytical model based on simplifying assumptions was used to estimate the heat losses in the well at different flow rates. This model cannot be used to estimate the pressure and temperature fields in the rock. Furthermore, it shows that a quasi-steady regime is reached in the well after a very long production time, which is not confirmed by practice.

A 3-D numerical model was defined and used to simulate the heat transfer, hydrodynamic and thermodynamic processes in the well and in the surrounding rock along the entire well. The computer code used for the numerical simulation was TOUGH2, PC version. The model was used to simulate the evolution of the pressure and temperature fields in the well and in the surrounding rock during artesian production at different flow rates. It showed that the quasi-steady regime in the well is reached after a relatively short time of constant flow rate production.

The results of the numerical model have been compared with those of the simplified analytical model, showing that the numerical model not only yields more information, but it also offers a more accurate estimation of the hydrodynamic and thermodynamic processes in the well.

1. THE ORADEA GEOTHERMAL RESERVOIR

Romania is located in Central Europe, North of the Balkan Peninsula, on the lower course of the Danube River, and on the Black Sea coast. The geological research carried out between 1960 and 1980 proved the existence of significant geothermal resources in some regions, mainly in the western part of the country. Over 200 drilled wells show the presence of geothermal resources, the proven reserves (by pumping the existing wells) being about 200,000 TJ for 20 years. The total installed capacity of the existing wells for energy uses is 320 MW_t (for a 30°C reference temperature). The main uses of geothermal energy in Romania are: space and tap water heating, greenhouse heating, health and recreational bathing, industrial process heat, and fish farming.

Oradea city is located in the western part of Romania, close to the Hungarian border. It has a population of about 250.000 people, and is the capital city of the Bihor County.

The Oradea geothermal reservoir comprises two specific aquifers that are hydraulically connected, namely: the Triassic aquifer Oradea and the Cretaceous aquifer Felix Spa. Although a significant recharge exists, the withdrawal rate of 300 l/s generates pressure draw-down in the system, that is prevented by partial reinjection. The total installed capacity is over 30 MW_t.

The Felix Spa reservoir is currently exploited by 6 wells, 50 to 450 m deep. The total artesian flow rate available from these wells is 210 l/s. The water is produced at a wellhead temperature of 36 to 48°C and is only used for recreational and health bathing.

The Oradea aquifer is located in Triassic limestone and dolomites, at depths of 2,200 to 3,400 m. The reservoir covers an area of about 113 km^2, and is exploited by 12 wells, with a total artesian flow rate of 140 l/s and well head temperatures of 70 to 105°C. The water is of calcium-sulphate-bicarbonate type, with no scaling or corrosion potential. There are no dissolved gases, and the TDS is lower than 0.9 to 1.2 g/l. The reservoir is bounded by faults. There are also internal faults in the reservoir, dividing it into four hydraulically connected blocks. The source of the geothermal fluid is located in the north-eastern part of the reservoir, along preferential pathways represented by the fault system at the boundary (Antics, 1996).

The terrestrial heat flow is about 90 mW/m^2, and the geothermal gradient 2.6-4.1°C/100 m. Properties such as ionic composition, high radioactivity and the content of rare gases, indicate an active circulation along paths partially in contact with the crystalline basement. The water is about 20,000 years old, the recharge area being in the Western Carpathian Mountains 20-30 km east of Oradea.

Based on all available data (geology, hydrology, well tests and logs, and production history) as well as on the reservoir simulation (Antics, 1996), the following mean values have been determined for the rock matrix:

- density: ρ_r = 2,750 kg/m^3;
- effective porosity: Φ = 1.8-2.0%;
- permeability: k_r = 230 mD;
- specific heat capacity: c_r = 1,030 J/kg·K;
- thermal conductivity:

λ_r = 3.72 W/m·K for Triassic dolomite;
λ_r = 3.00 W/m·K for Triassic limestone;
λ_r = 2.79 W/m·K for Lower Cretaceous limestone;
λ_r = 3.20 W/m·K for Upper Cretaceous limestone;

- transmissivity: T = 211 D·m.

2. THE GEOTHERMAL WELL COMPLETION

The geothermal well from the University of Oradea campus was completed in 1981 and initially produced in artesian discharge 2.5 l/s geothermal fluid with a wellhead temperature of 68°C. After the acid job carried out in 1983 (1,500 m^3 of 1.5% HCl solution), the artesian flow rate increased to 31 l/s, and the well head temperature reached 85°C. The well is producing, at different flow rates, almost continuously since the acid job of 1983.

The well from the University of Oradea campus (as most of the wells in Romania) was usually logged twice per year, in spring and in autumn. All pressure and temperature logs between 1981 and 1995 were compared and analyzed, the most reliable being considered the latest, of July 30, 1995, this being the only time when electronic gauges were used to log the well, both in static and dynamic conditions.

Figure 1 shows the completion of the geothermal well and the geological strata identified during drilling. The casings ($13^3/_8$", $9^5/_8$", and 7") are cemented. The 7" production tubing was removed in 1996, when a line shaft pump was installed in the well to increase the production flow rate to 50 l/s.

Detailed data on the well completion, as well as the thermal and hydraulic properties of the geothermal fluid, casings, cement, and rocks from all the geological strata identified during drilling (calculated based on static temperature logs) are presented by Rosca and Antics (1999).

3. THE ANALYTICAL MODEL

The Oradea geothermal aquifer comprises a number of layers with different thermal and hydraulic properties. The main feed zone of the well s is at the depth of about 2,500 m. Less important feed zones are distributed between 2,200 and 2,800 m. Therefore, as the fluid flows upwards in the opened interval, the flow rate increases and the temperature decreases, due to the inflow of colder fluid from shallower layers. In the cased part of the well (above the reservoir), the fluid loses heat through the casings and cement to the surrounding rocks. The aim of the calculations was to determine, for different flow rates, the heat loss and, consequently, the temperature field in the well as a function of depth (h [m]) and time (τ [s]).

The analytical model used for these calculations is described by Ortiz-Ramirez (1983), based on the methodology and assumptions proposed by Ramey (1962).

A simplifying assumption is that the thermal resistance due to the convective heat transfer from the fluid to the casing is negligible as compared the conductive heat transfer through the heterogeneous cylindrical wall of an infinite outer radius, (which means that the fluid and inner surface of the casing are assumed to have the same temperature). Furthermore, the diameter of the well is usually much smaller than its length for the depth intervals used in calculations of this type (over which a rock layer may be accepted as homogeneous).
The above mentioned initial assumptions justify the use of a simplified model for the conductive heat transfer through a cylindrical wall of infinite radius, as briefly described below.

At a given depth, for a (Δt [°C]) temperature difference between the casing and the outer rock (far enough not to be influenced by the heat transfer process) the heat flux density ($\dot{q}$ [W/m^2]) through the inner surface of the casing may be expressed in the following two different asymptotic forms:

- for small production times:

$$\dot{q} = \frac{\lambda \cdot \Delta t}{r} \cdot \left[(\pi \cdot \tau')^{-1/2} + \frac{1}{2} - \frac{1}{4} \cdot \left(\frac{\tau'}{\pi} \right)^{1/2} + \frac{1}{8} \cdot \tau' - \cdots \right] \quad (1)$$

- for large production times:

$$\dot{q} = \frac{2 \cdot \lambda \cdot \Delta t}{r} \cdot \left\{ \frac{1}{\ln(4\tau') - 2\gamma} - \frac{\gamma}{[\ln(4\tau') - 2\gamma]^2} - \cdots \right\} \quad (2)$$

where: λ [W/m·K] - thermal conductivity of the surrounding rock;
Δt [°C] - the temperature difference between the rock and the geothermal fluid;
r [m] - inside radius of the casing;
γ = 0,5772 [-] - Euler's constant;
τ' [-] - nondimensional time (equivalent to the Fourier number), defined as:

$$\tau' = \frac{a \cdot \tau}{r^2} \quad (3)$$

The total heat flux ($\dot{Q}$[W]) transferred through the inner surface of the casing to the surrounding rock along the depth interval Δh [m] is:

$$\dot{Q} = 2\pi \cdot r \cdot \Delta h \cdot \dot{q} \quad (4)$$

The heat flux transferred along a depth interval is calculated as a function of the temperature difference between the fluid and the rock. The depth intervals are defined, bottom to top, according to the rock formations identified during drilling, and the rock in each interval is assumed to be homogeneous. The rock temperature is then the natural state temperature at the middle of each interval. The mean temperature of the geothermal fluid being a function of the heat flux lost along the depth interval, these values are calculated by iteration.

The time steps have been selected to increase in geometrical progression with the ratio 10. For the specific parameters of the well from the University of Oradea campus, equation 1 does not converge for times smaller than 10^2 and larger than 10^5 s, while equation 2 does not converge for times smaller than 10^5 s.

Calculations have been carried out (in Microsoft Excel) for some flow rates for which temperature logs were available. The calculated temperature profiles at different times and the experimental data for the flow rates of 14.5 l/s and 30 l/s are given in figures 2 and 3 respectively. A good correlation was obtained between the calculated and measured data for the flow rate of 14.5 l/s, but not for 30 l/s. This is mainly caused by the inaccuracy of the experimental values for the latter, a mechanical gage being used for that temperature log, while for the first an electronic gage was used.
These graphs show that the thermal regime in the well tends to become quasi-steady after a constant production time which decreases with flow rate. For 14.5 l/s the quasi-steady regime is reached after about 10^9 s (30 years). For 30 l/s, the changes are insignificant after 10^8 s (3 years) of production.

Experience shows that the production time after which the quasi-steady regime is attained is much shorter than the one calculate by the analytical model.

The analytical model cannot accurately represent the lower part of the well, which is open to a reservoir comprising layers of different porosity and thickness, along which the flow rate is increasing with variable ratios, depending on the rock porosity. Furthermore, the analytical model cannot take into account the variation with temperature of the thermal and hydraulic properties of the materials involved in the heat transfer process, and it cannot calculate the temperature field in the surrounding rock as a function of radius and time.

For these reasons, the analytic model is only giving an approximate evaluation of the temperature distribution along the well as a function of flow rate and time. To obtain more data on the pressure and temperature fields in the well and surrounding rock it was considered useful to set up a numerical model.

4. THE NUMERICAL MODEL

The PC version of the TOUGH2 computer code was used to model the low enthalpy geothermal well from the University of Oradea campus.

A cylindrical model was defined, with the external radius of 10 km, for the outermost elements certainly not to be affected by the heat exchange with the geothermal fluid flowing in the well, and also for the modeled reservoir to be about the same size as the real one (in surface and thickness), although not the same shape.

For the natural state simulation, the model was divided into 36 cylindrical blocks on top of each other. The thickness of each block was selected so that the block could be considered homogeneous and the center of most of them to correspond to usual measurement points used during temperature logging.

Two more blocks were added, on top and below. The top block was defined to simulate the atmosphere, with zero volume for constant pressure and temperature conditions (for the Oradea area, annual mean values of 1 bar and 10.2°C). The bottom block was defined as very thin, with thermal and hydraulic properties of an impermeable rock, to supply the natural heat flow of 90 mW/m^2.

Each of the 36 rock blocks was then divided into 28 coaxial cylindrical blocks. The radial increment was smaller for the first 18 blocks and selected such as to correspond to the well completion (casings, cement, and borehole). To simulate the well head, a block was defined on top of the well, with hole properties, separated from the atmosphere by a steel block.

More details on the model and its natural state, static and dynamic calibration are given by Rosca and Antics (1999).
After the model's calibration, artesian production at full flow has been simulated for 10^8 s (about 3 years). The simulated parameters (volume flow rate, wellhead pressure, and wellhead temperature) are shown in Figure 4. The graph shows three distinct stages of the well's evolution in time.

During the first stage, which lasts $6\text{-}7{\cdot}10^3$ seconds (about 2 hours), cold fluid is discharged from the well and replaced by the hot fluid flowing in from the reservoir. In the first few seconds after the wellhead valve is fully opened, due to the water's incompressibility, the wellhead pressure falls from 2.28 bar (the stabilized static regime value), down to 0.8 bar. Thus, the well can only be started by gradually opening the valve, which corresponds to the real situation. As the hot fluid is replacing the cold one in the well, the hydrostatic pressure decreases, and therefore the wellhead pressure increases, reaching a maximum after about $2{\cdot}10^3$ seconds. Then, the wellhead pressure slightly decreases as the pressure drop in the rock around the well increases due to the rapid increase of the flow rate. During this stage, when the wellbore storage effect is dominant, both the hydraulic and thermal regimes are highly transient, the pressure and temperature fields varying at a fast rate, mainly in the blocks defined inside and close around the well.

The thermal and hydraulic regimes in the second stage are also transient, but the temperature and pressure variations are much slower, both in the well and surrounding rock. The wellhead temperature increases by less than 2°C during 200 days of full flow production. The artesian flow rate continues to slowly increase, due to hydrostatic pressure decrease, then starts to decrease, as does the wellhead pressure, due to the reservoir pressure decrease.

The temperature and pressure profiles in the well, and the heat flux lost to the surrounding rock do not significantly vary during this stage, because the casing, the cement, and the rocks close to the well are already heated, and as the heat exchange area increases with the square of the radius, so that the heat flux density (W/m^2) tends to become negligible at a few tens of meters from the well. Therefore, both the thermal and hydraulic regimes in the well may be considered as quasi-steady during this second stage.

The third stage starts after about $2{\cdot}10^6$ s. The artesian flow rate and the wellhead pressure are both decreasing relatively fast, due to the depletion of the modeled reservoir, which is closed, unlike the real one. As the main target was to model the well, and not the reservoir, this stage has no real meaning. It only confirms once again that the simulator works correctly. It may also be used to calibrate a full model of the reservoir, including all wells and its border conditions, such as natural recharge.

During the first discharge stage, when the wellbore storage effect is dominant, the temperature of the inner surface of the casing is rapidly increasing, and therefore the heat flux lost to the surrounding rock is decreasing. During the second stage the temperature increase of the inner casing surface and decrease of the lost heat flux become almost negligible, so that, again, the thermal regime may be considered as quasi-steady, as shown in Figure 5 for full flow rate production.
Based on the numerical simulation results, it was possible to calculate that during the quasi-steady state, the coefficient of convection in the well varies by less than 1% with depth and time, being essentially only a function of the fluid velocity. For a flow rate of 30 l/s, the flow velocity in the 7" casing is 1.19 m/s and the convection coefficient 18 W/m^2·K, while in the $9^5/_8$" casing the velocity is 0.61 m/s and the convection coefficient 6.5 W/m^2·K.

The simulator calculates the pressure and temperature values in the center of each block defined in the model at the time steps set in the input file. Figure 6 shows the evolution of the temperature field in the center of the blocks around the well, at the depth of 400 m. After about 3 years of production at 30 l/s, the temperature increase in the next block (50 m from the well axis) is less than 1°C. Therefore, it may be accepted that, after 20-30 years of production, the temperature will not be significantly modified at 100 m from the well.

For the heterogeneous cylindrical gridblocks located 100 m from the well, the highest value of the thermal resistance for conduction was obtained for the layer with the center at the depth of 400 m (having both 7" and $9^5/_8$" cemented casings), namely 1.32 m·K/W, and the lowest was 1.12 m·K/W. The thermal resistance for convection along the same layers were 0.625 m·K/W and 0.313 m·K/W respectively. In general, for the above mentioned conditions, the thermal resistance for convection is about 20-25% of the thermal resistance for conduction, which is not at all negligible.

The calculated wellhead temperature for different flow rates is shown in Figure 7. Because the wellhead temperature slowly increases, even during the quasi-steady regime, production was simulated for 2 to 10 days (or longer for smaller flow rates), thus reaching the quasi-steady regime and also avoiding the occurrence of a significant pressure drop in the modeled reservoir. Based on the simulated values, it was possible to find the following equation of the wellhead temperature as a function of the production volume flow rate:

$$t_{WH} = 66.444 + 1.791\dot{V} - 5.278 \cdot 10^{-2}\dot{V}^2 + 5.144 \cdot 10^{-4}\dot{V}^3 \quad (5)$$

where: t_{WH} [°C] - well head temperature;
$\dot{V}$ [l/s] - volume flow rate.

Equation 5 may confidently be used to estimate the well head temperature of the modeled well even for production flow rates at least 50% higher than the maximum artesian one, which would represent the installation of a deep well pump to increase production. For a more accurate estimate, a new model has to be set up, which should include the model of the specific pump to be installed in the well.

The simulation results have also been used to obtain the deliverability curve for the modeled well (wellhead pressure as a function of the production flow rate), as well as the deliverability equation (same methodology as for Figure 7 and Equation 5). These may be used to estimate the depth at which a certain pump should be set in the well.

For the quasi-steady regime, Figure 8 shows the total heat flux lost in the well and the specific heat loss per unit mass (calculated as the ratio between the heat flux and the mass flow rate) as functions of mass flow rate. At small flow rates, the specific heat loss and therefore the specific enthalpy decrease along the well is more significant, resulting in a more severe temperature decrease, a lower average temperature in the well, and thus a lower value for the total heat flux lost in the well.

As the flow rate increases, the fluid velocity in the well and the convection coefficient also increase, therefore the total lost heat flux increases, whereas the specific heat loss and the specific enthalpy drop decrease, resulting in a lessening of the temperature drop in the well, therefore a higher average temperature in the well and a higher wellhead temperature.

In low enthalpy wells, in which boiling cannot occur, it is possible that there would only be a small specific enthalpy drop along the well (due to the specific heat loss) at high flow rates. Therefore, as the hydrostatic pressure decreases with depth, the fluid temperature does not decrease, but slightly increase. For the modeled well, at a flow rate of 30 l/s, the temperature in the cased part of the well(above the reservoir) increases by about 1°C before decreasing again close to the wellhead.

5. CONCLUSIONS

The analytical model gives an approximate evaluation of the temperature distribution along the well as a function of flow rate and time. On the other hand, the numerical model of a low enthalpy geothermal well, provides data useful for the study of all the thermal and hydrodynamic processes occurring in low enthalpy wells and in the surrounding rocks, from the reservoir up to surface.

After the static and dynamic calibration of the 3D model, it is possible to simulate any desired production or injection scenario and to obtain the evolution in time of the pressure and temperature fields in the well and in the surrounding rocks. The fluid flow rate and heat flux transferred between each pair of blocks of the defined model can also be simulated. It is then possible to find the influence of the mass or volume flow rate on wellhead pressure, wellhead temperature, total heat flux lost in the well, specific heat loss, specific enthalpy drop, etc.

It was also possible to verify the assumption proposed by Ramey (1962), and adopted by Ortiz-Ramirez (1983), that the thermal resistance of convection in the well is negligible compared to the thermal resistance of conduction in a cylindrical wall of infinite radius. The assumption is obviously true for an infinite radius cylindrical wall, but the numerical simulation shows, at least for a low temperature system, that the temperature field in the rock at 100 m from the well is not perturbed after 30 years of full flow production. In these conditions, the thermal resistance of convection is not negligible, being about 20-25% of the thermal resistance of conduction in a 100 m thick cylindrical wall.

TOUGH2 is a useful tool not only for modeling underground fluid reservoirs, but also for modeling individual wells. Therefore, it is possible to set up a full 3D model of the reservoir and all the wells, which would be very useful for an efficient management of the reservoir.

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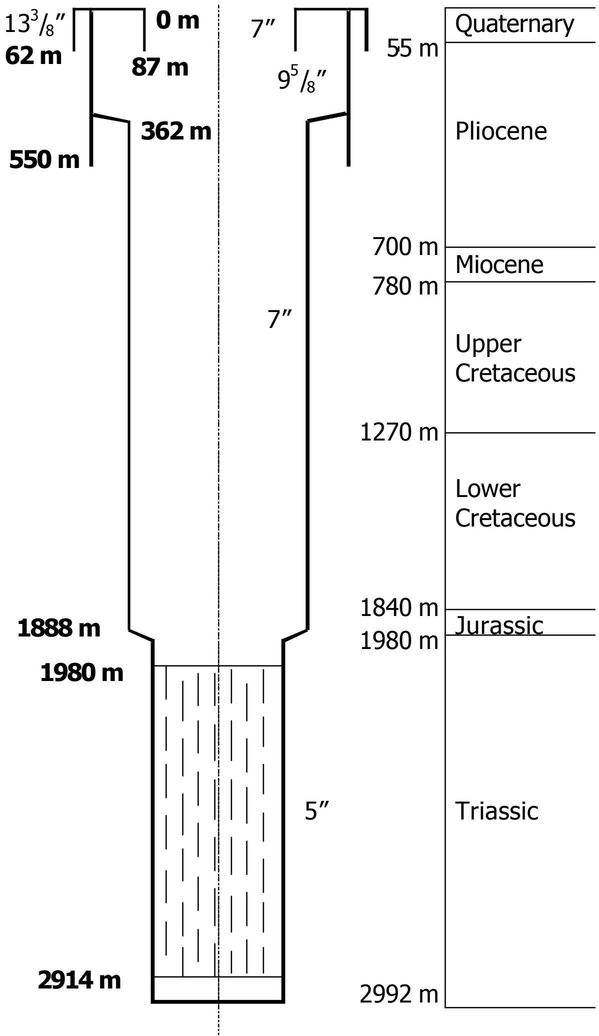

Figure 1: Well completion and geological strata

Rosca, M., and Antics, M. (1999). Numerical Model of the Geothermal Well Located at the University of Oradea Campus. *Proceedings of the 24th Geothermal Reservoir Engineering Workshop*, SGP-TR-162, Stanford, CA.

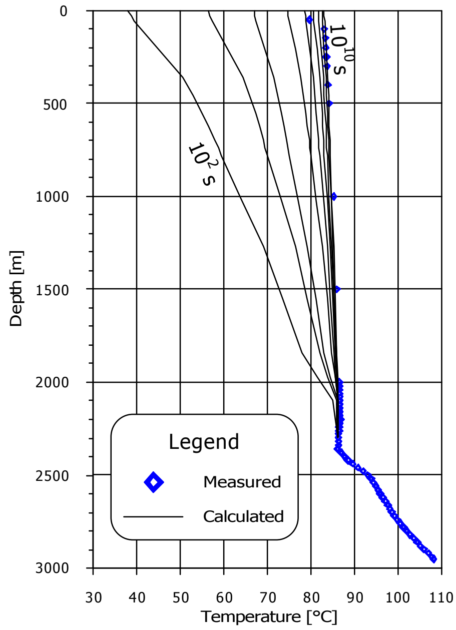

Figure 2: Measured and analytical model results for 14.5 l/s

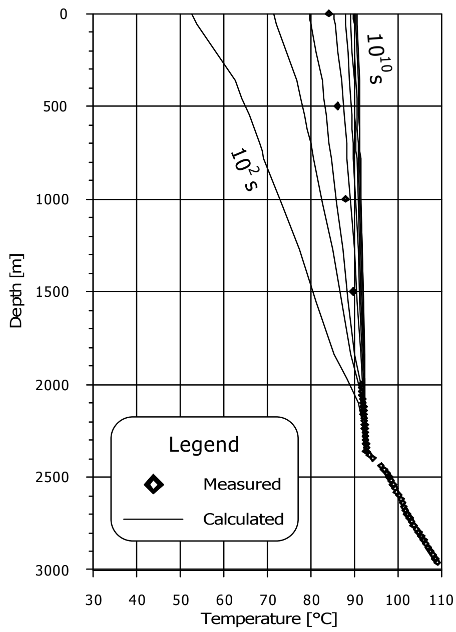

Figure 3: Measured and analytical model results for 30 l/s

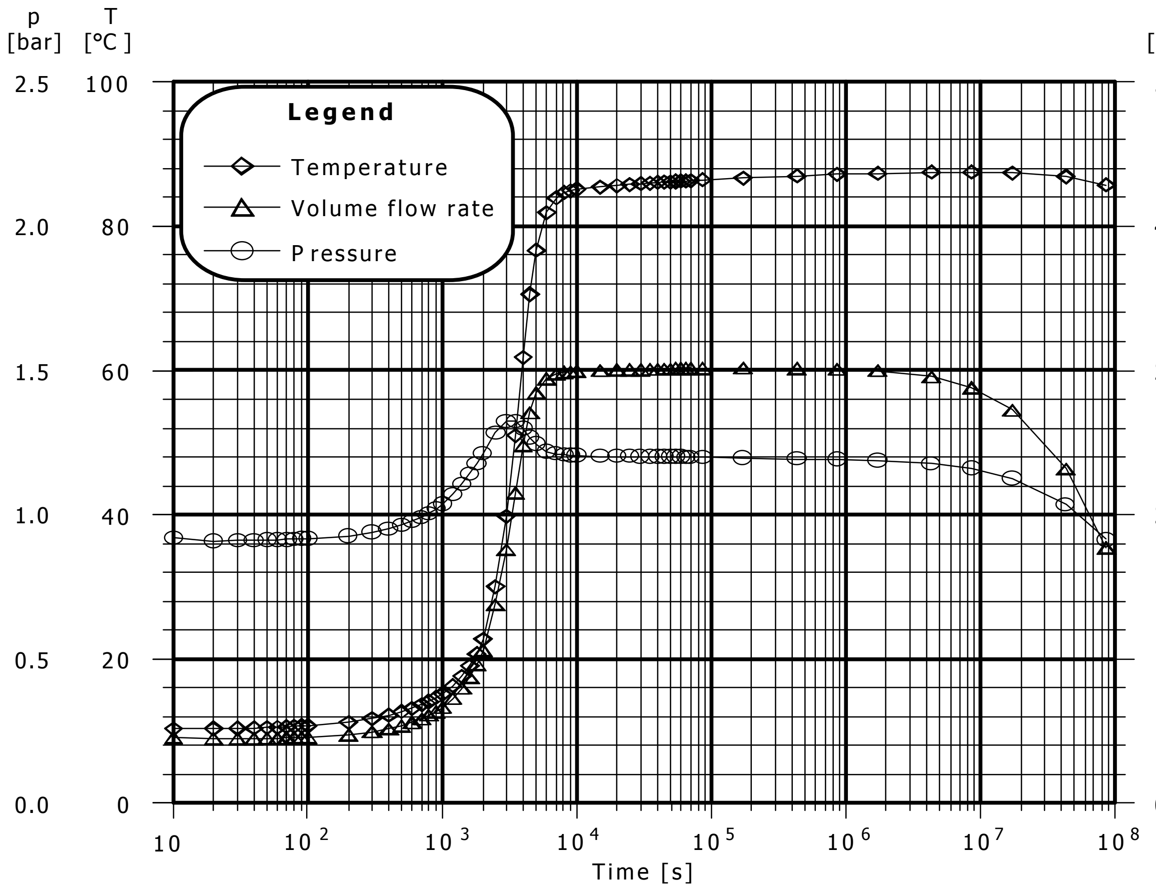

Figure 4: Simulated volume flow rate, well head pressure, and well head temperature for full artesian flow

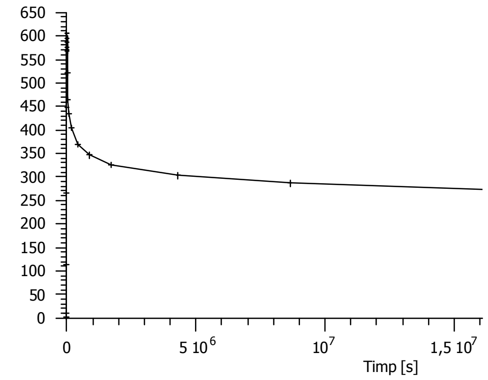

Figure 5: Total heat flux lost in the well above the reservoir for maximum artesian flow rate (30 l/s)

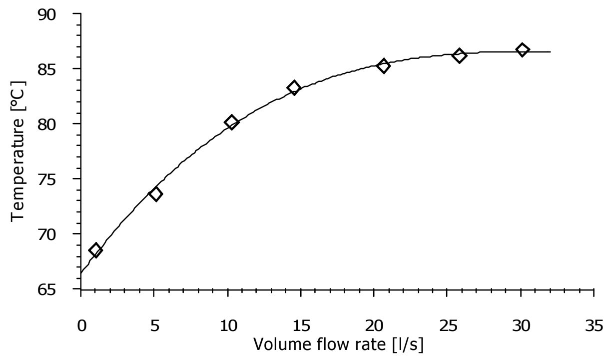

Figure 7: Well head temperature variation with flow rate

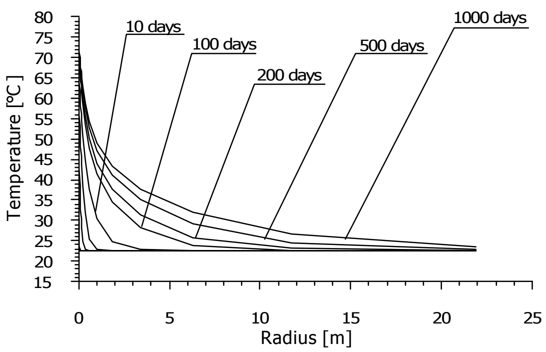

Figure 6: Temperature field at the depth of 400 m

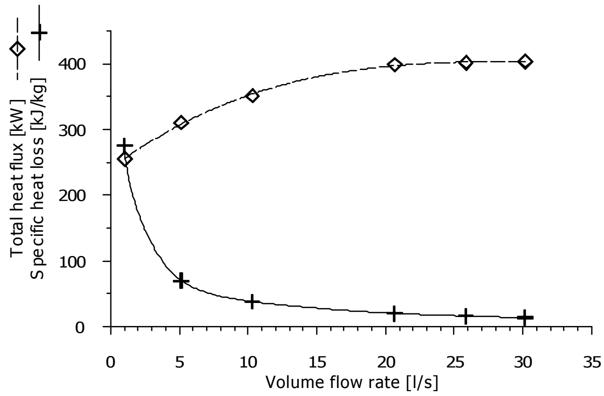

Figure 8: Heat loss as a function of flow rate