

NUMERICAL MODEL OF THE GEOTHERMAL WELL LOCATED AT THE UNIVERSITY OF ORADEA CAMPUS

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ABSTRACT

The well from the University of Oradea campus is a typical low enthalpy geothermal well, about 3,000 m deep, 80÷85°C wellhead temperature, and multiple feed zones. A 3-D numerical model has been defined and used to simulate the heat transfer and the hydrothermodynamic processes in the well and in the surrounding rock along the entire well.

The paper presents the model's grid, the thermal and hydrodynamic properties of each block, the natural state simulation, the static and dynamic calibrations, and some preliminary results for artesian discharge.

THE ORADEA GEOTHERMAL RESERVOIR

Romania is located in Central Europe, North to 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 proved reserves (with the already drilled wells exploited by downhole pumps) are 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 are: space heating and domestic hot water, greenhouse heating, health and recreational bathing, industrial process heat, and fish farming.

The City of Oradea is located in the Western part of Romania, close to the Hungarian border, 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, hydrodynamically connected via fractures, the Triassic aquifer Oradea and the Cretaceous aquifer Felix Spa respectively. Although a significant natural recharge exists, the exploitation with a total flowrate of 300 l/s generates pressure drawdown in the system, that is prevented by reinjection. The total installed capacity is over 30 MW_t.

The Felix Spa reservoir is currently exploited by 6 wells, 50÷450 m deep. The total flowrate available from these wells is 210 l/s. The geothermal water has wellhead temperatures of 36÷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÷3,400 m, on an area of about 113 km², and is exploited by 12 wells, with a total artesian flowrate of 140 l/s and wellhead temperatures of 70÷105°C. The water is of calcium-sulfate-bicarbonate type, with no scaling or corrosion potential. There are no dissolved gases, and the mineralisation is lower than 0.9÷1.2 g/l. The reservoir is bounded by faults. There are also internal faults in the reservoir, dividing it into four blocks which do not cause discontinuities in the circulation of the water in the reservoir. The main circulation is from the north-eastern part of the reservoir, along preferential pathways represented by the fault system at the boundary (Figure 1).

The terrestrial heat flow is about 90 mW/m², and the geothermal gradient 2.6÷4.1 °C/100m. 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.

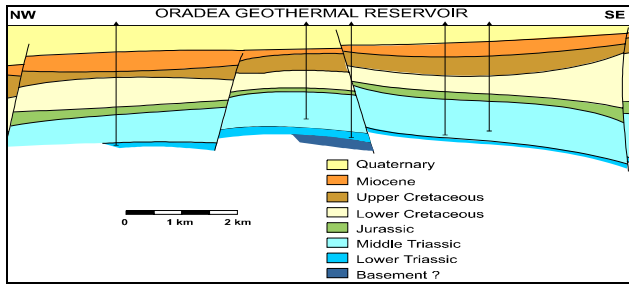


Figure 1: Cross section through the Oradea reservoir

A reservoir simulation has been carried out for the Oradea geothermal reservoir, using the TOUGH2, PC version, computer code, developed by K. Pruess at the Earth Science Division, Lawrence Berkeley Laboratory, University of California (Antics, 1996).

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

- density: $\rho_r = 2,750 \text{ kg/m}^3$;
- effective porosity: $\Phi = 1.8 \div 2.0\%$;
- permeability: $k_r = 230 \text{ mD}$;
- specific heat capacity: $c_r = 1,030 \text{ J/kg}\cdot\text{K}$;
- thermal conductivity:
 - $\lambda_r = 3.72 \text{ W/m}\cdot\text{K}$ for Triassic dolomite;
 - $\lambda_r = 3.00 \text{ W/m}\cdot\text{K}$ for Triassic limestone;
 - $\lambda_r = 2.79 \text{ W/m}\cdot\text{K}$ for Lower Cretaceous limestone;
 - $\lambda_r = 3.20 \text{ W/m}\cdot\text{K}$ for Upper Cretaceous limestone;
- transmissivity: $T = 211 \text{ D}\cdot\text{m}$.

THE GEOTHERMAL WELL COMPLETION

The geothermal well from the University of Oradea campus has been completed in 1981 and produced in artesian discharge 2.5 l/s geothermal fluid with a well heat temperature of 68°C. After the acid job carried out in 1983 (1,500 m³ of 1.5% HCl solution), the artesian flowrate increased to 31 l/s, and the wellhead temperature reached 85°C.

The completion of the geothermal well from the University of Oradea campus is shown in Figure 2, together with the geological strata identified during drilling. The casings (13³/₈"", 9⁵/₈"", 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 flowrate to 50 l/s.

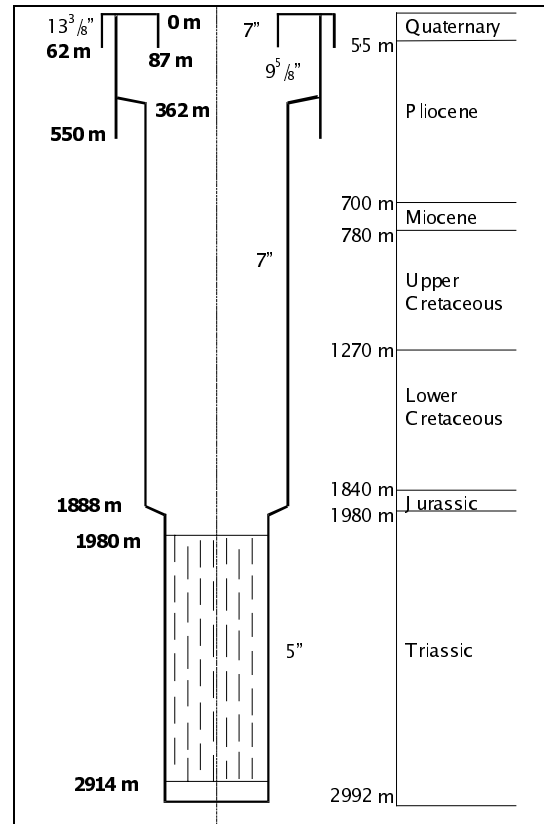


Figure 2: Well completion and geological strata

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 stations of well logs.

Two more blocks were added, one on top and the other 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/m².

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 wellhead, one block was defined on top of the well, with hole properties, separated from the atmosphere by a steel block.

Table 1 gives the thermal and hydraulic properties of all the materials defined for the blocks, as resulted after the static and dynamic calibrations.

Table 1: Hydrothermal properties of materials

	Density ρ [kg/m ³]	Porosity Φ [-]	Permeability k [m ²]	Thermal Conductivity λ [W/m·K]	Heat capacity c [J/kg·K]
1	1,800	0.30	1.00E-12	2.667	871.6
2	1,900	0.30	1.00E-12	2.989	885.6
3	1,950	0.25	5.00E-13	2.821	892.7
4	2,000	0.20	5.00E-13	2.621	906.1
5	2,000	0.20	5.00E-13	2.751	911.3
6	2,100	0.10	1.00E-13	2.761	914.2
7	2,200	0.15	2.00E-13	2.777	917.6
8	2,300	0.10	2.00E-13	2.789	919.7
9	2,500	0.05	1.00E-20	2.871	923.3
10	2,750	0.10	1.00E-20	3.212	1,030.0
11	2,750	0.10	6.00E-13	2.253	1,030.0
12	2,750	0.10	5.00E-20	2.277	1,030.0
13	2,750	0.10	4.00E-15	2.797	1,030.0
14	2,750	0.10	1.60E-12	1.827	1,030.0
15	2,750	0.10	4.00E-14	3.112	1,030.0
16	2,750	0.10	7.50E-14	2.277	1,030.0
17	2,750	0.10	2.30E-14	2.797	1,030.0
18	2,750	0.10	8.00E-14	3.112	1,030.0
19	2,750	0.10	0	2.277	1,030.0
20	1.12	0.9999	5.00E-11	0	1,000.0
21	1,000	0.9999	1.80E-06	0.800	4,200.0
22	7,850	0.00	0	54	477.0
23	2,250	0.01	1.00E-20	2.836	760.0

The numbers represent, respectively:

1. Quaternary (1);
2. Quaternary (2);
3. Upper Pliocene;
4. Lower Pliocene (1);
5. Lower Pliocene (2);
6. Miocene;
7. Upper Cretaceous;
8. Lower Cretaceous;
9. Jurassic;
10. Triassic (1);
11. Triassic (2);
12. Triassic (3);
13. Triassic (4);
14. Triassic (5);
15. Triassic (6);
16. Triassic (7);
17. Triassic (8);
18. Triassic (9);
19. Bottom;
20. Air;
21. Well hole;
22. Steel;
23. Cement.

MODEL CALIBRATION

The initial conditions for the natural state simulation were selected equal to the annual mean atmospheric conditions (1 bar and 10.2°C), constant with depth. The thermal regime stabilized after about 1.2 million years, which is practically the approximate time of the geological evolution of the reservoir. Figures 3a and 3b show the simulated temperature and pressure fields in the natural state.

The pressure and temperature fields in the natural state have been used as initial condition for the next stage, the simulation of the stabilized static regime of the geothermal well, when it is closed and in thermal equilibrium with the surrounding rock.

The simulated thermal equilibrium is reached after about 3 hours. This time has no real meaning, as the simulation did not consider the pressure, and mainly the temperature, fields perturbation during drilling. The stabilized static regime simulation is needed to define the initial conditions in each block.

In stabilized static regime, the simulated difference between the temperature of the fluid inside the well and the rock temperature at the same depth (in the natural state) does not exceed 0.1°C. As regarding the pressure, the difference is more significant. In Figure 3b the well pressure is represented with “+”, the continuous curve representing the natural state pressure field.

The production history, starting after the acid job in 1981 until 30 August 1995, the date of the well logs used for both static and dynamic regime calibrations, is shown in Figure 4.

When running the simulator for the production history, a rapid pressure decline started after about one year,

due to the facts that the model's reservoir has no natural recharge, unlike the real one, and the reservoir temperature is too low to start boiling. This behavior confirms that the simulator works correctly. The envisaged purpose was to model the hydraulic and thermal processes in the well, and not the real reservoir.

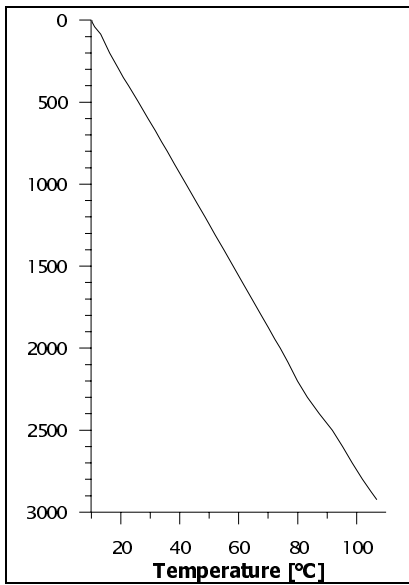


Figure 3a: Temperature field in the natural state

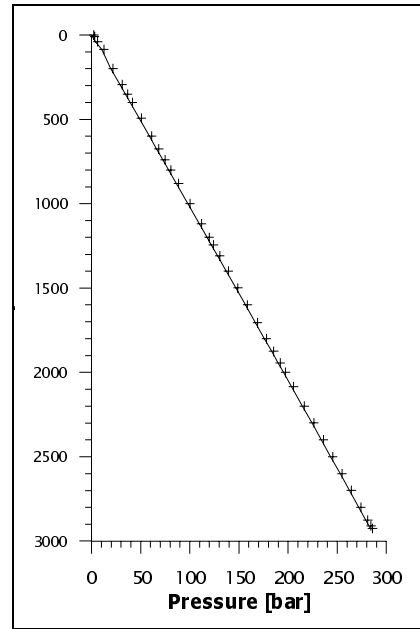


Figure 3b: Pressure field in the natural state

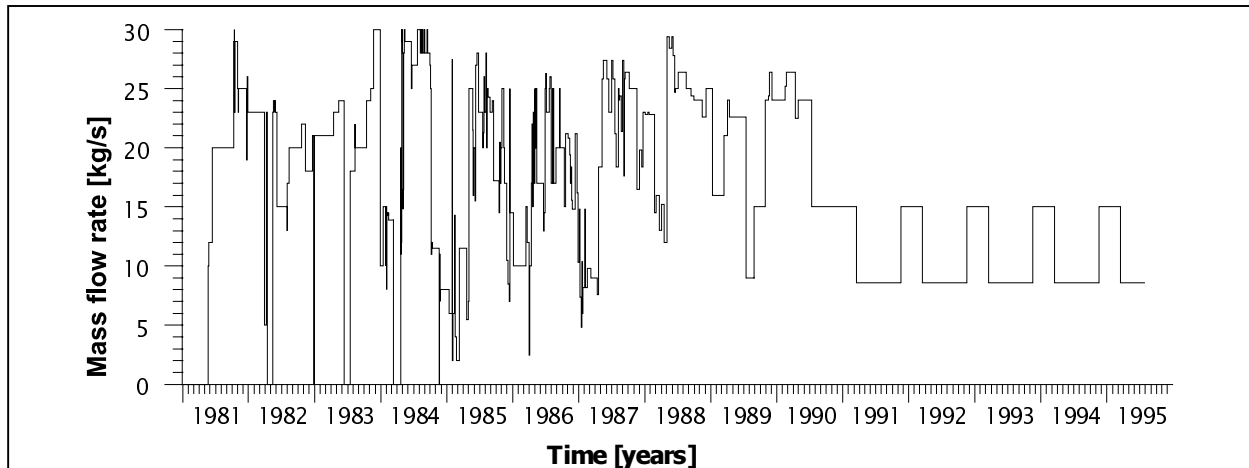


Figure 4: Production history

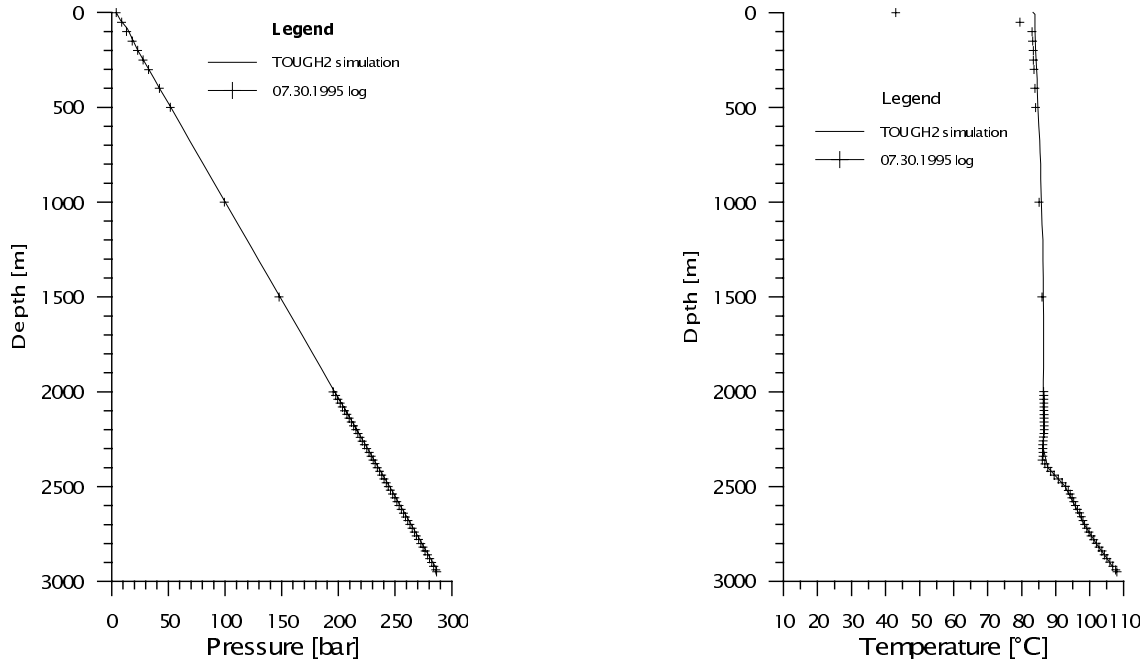


Figure 5: Dynamic pressure and temperature calibration

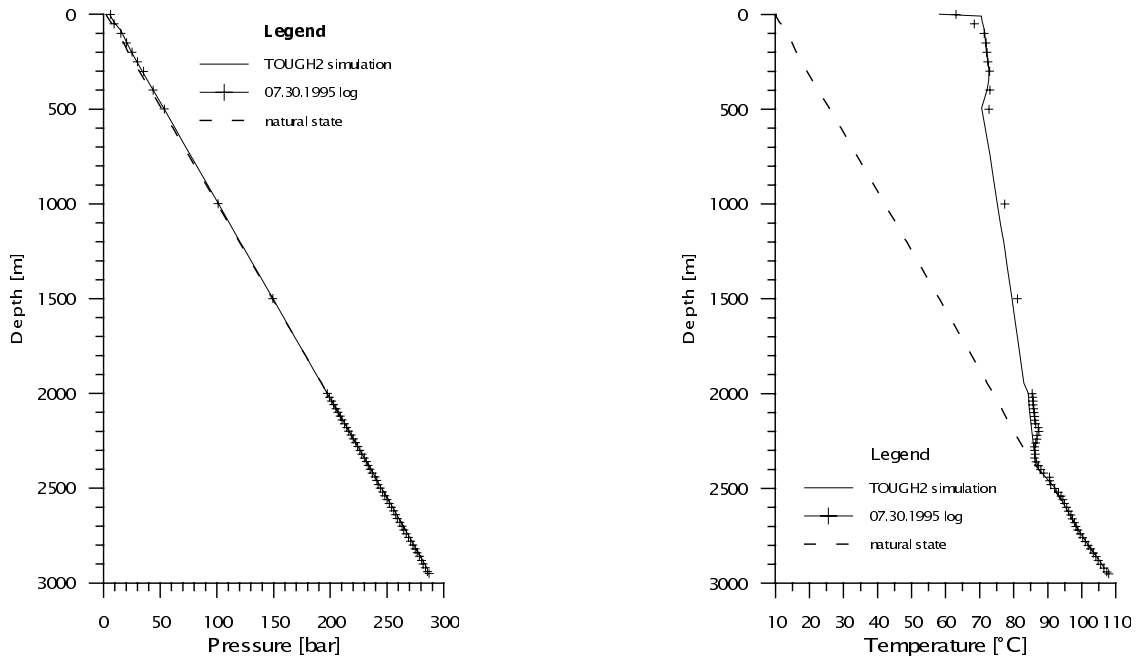


Figure 6: Static pressure and temperature calibration

Therefore, observing that the temperature field is modifying at a low rate after about 200 days of production at the maximum artesian flowrate (about 30 l/s), this scenario was accepted, instead of the production history, for the model's calibration. The well logs of August 1995 have been used for both dynamic and static calibrations of the model,

these being the only ones for which electronic gauges were used, therefore having a reliable accuracy. For the dynamic condition logging the well produced 14.5 l/s (in artesian discharge). The well was then closed for 6 hours. To compare the calculated pressure and temperature values in the well with the measured ones, for the dynamic calibration a 14.5 l/s

production was simulated for 24 hours. Then, for the static calibration, the closed well was simulated for the next 6 hours. The dynamic calibration is shown in Figure 5, and the static one in Figure 6.

The correlation between the calculated and measured data is very good for the lower part of the well, along the reservoir, where measurement points are closer to each other, as this is the main interest part for the hydrodynamic investigation of the reservoir. It was therefore possible to have a more accurate selection of the thermal and hydraulic parameters of the rock matrix in the vicinity of the modeled well.

For the dynamic calibration, significant errors occur at the upper part of the well, mainly due to the fact that at the logging date (August 1995, before the line shaft pump was installed) the well had a 5¹/₂" tubing down to 200 m. This was not included in the model, as TOGH2 does not calculate the heat exchange by radiation, and the production tubing was removed when the line shaft pump was installed in the well.

The following conclusions have been reached from the calibration process:

- for a given terrestrial heat flow, the temperature

field in the natural state mainly depends of the thermal conductivity of the rocks;

- the pressure field in the natural state mainly depends of the temperature field, and at a smaller extend of the rocks' porosity;
- in the stabilized static regime, the temperature in the well is almost equal to the rock temperature at the same depth;
- the pressure profile in the well is mainly influenced by the pressure field in the reservoir, less by temperature field, and not at all by the pressure field in the rock above the reservoir, with which it has no hydraulic connection;
- in the same pressure and temperature conditions, the artesian flowrate is severely influenced by the "permeability" inside the well, which quantifies the hydrodynamic losses in the well.

SOME SIMULATION RESULTS

After the model's calibration, artesian production at full flow has been simulated for 10⁸ s (about 3 years). The simulated parameters are shown in Figure 7.

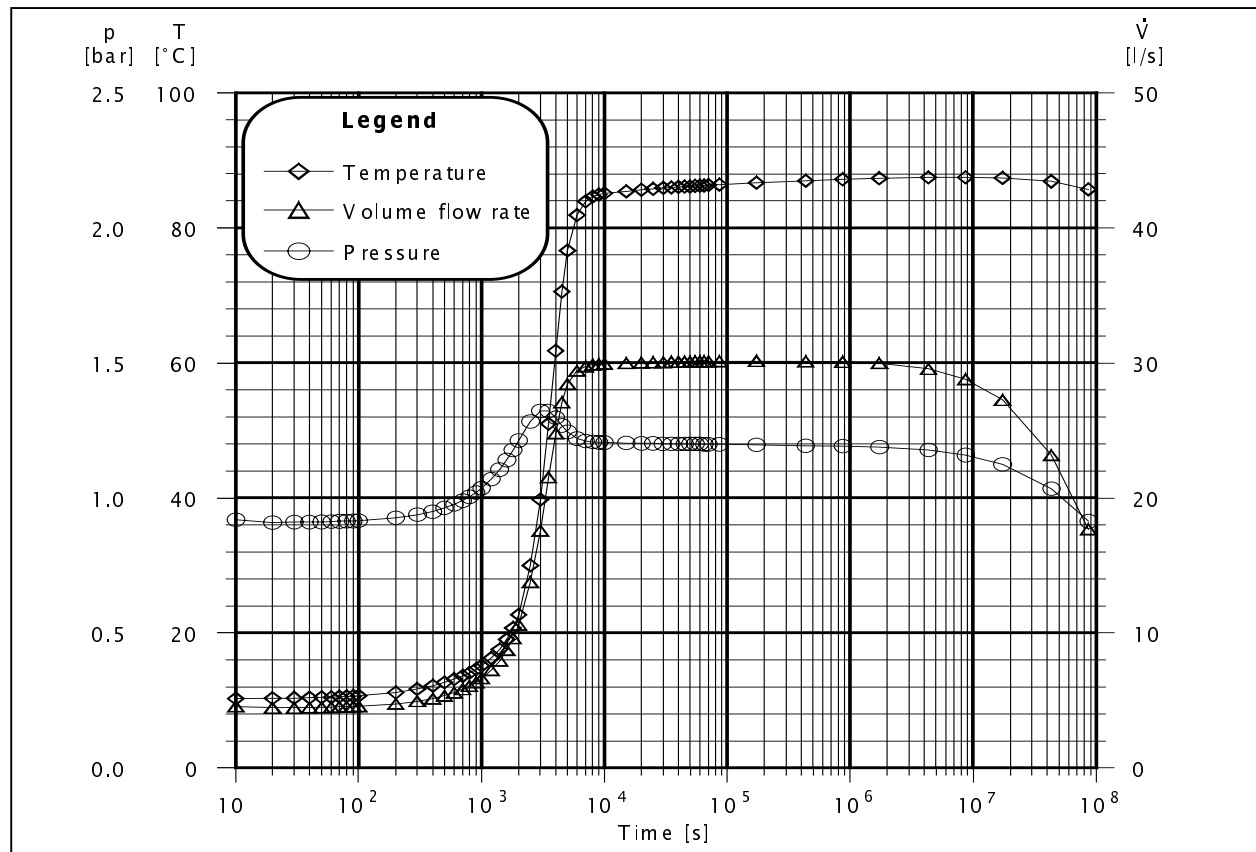


Figure 7: Simulated flowrate, wellhead pressure, and wellhead temperature for full artesian flow

The graph presented in figure 7 shows three distinct stages of the evolution in time of the well.

During the first stage, which lasts $6\div 7 \cdot 10^3$ seconds (about 2 hours), the cold fluid is removed from the well, being 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 value in stabilized static regime), 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, therefore the wellhead pressure increases, reaching a maximum after about $2 \cdot 10^3$ seconds. Then the wellhead pressure decreases slightly as the pressure drop in the rock around the well increases due to the rapid increase of the flowrate. During this stage, when the wellbore storage effect is dominant, both the hydraulic and thermal regimes are highly transitory, 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 transitory, but the temperature and pressure variations are much slower, both in the well and surrounding rock. The wellhead temperature increases with less than 2°C during 200 days of full artesian flow production. The artesian flowrate continues to slowly increase, due to hydrostatic pressure decrease, then starts to decrease, as well as 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 vary significantly 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.

Based on the numerical simulation results, it was possible to calculate that during the quasi-steady state the coefficient of convection in the well vary by less than 1% with depth and time, being only function of the fluid velocity. For the full artesian flow, it was about $18 \text{ W}/\text{m}^2\cdot\text{K}$ in the $9\frac{5}{8}$ " casing, and $6.5 \text{ W}/\text{m}^2\cdot\text{K}$ in the 7" casing. Furthermore, it was possible to

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

The third stage shows in figure 7 after about $2 \cdot 10^6$ s. The artesian flowrate 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 boundary conditions, such as natural recharge.

CONCLUSIONS

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

The numerical model of a low enthalpy geothermal well presented above, actually the one from the University of Oradea campus, provides data useful for the study of all the thermal and hydrodynamic processes occurring in the wells and surrounding rocks, from the reservoir up to surface.

A model calibration based on accurate measured data provides good estimates of the thermodynamic and hydrodynamic properties of all materials, including casings and cement, being even possible to identify some problems, such as scaling and corrosion in the well (from pressure losses), or cracks in the cement (from heat losses).

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