GeoWell

v. 1.1

Geothermal well calculator
User guide

Authors:

Leszek Pająk
Karol Pierzchała
Maciej Miecznik

Mineral and Energy Economy Research Institute
Polish Academy of Sciences

December 2024

This guide is the result of the implementation of the project "Optimal management of low-temperature geothermal reservoirs – Polish-Icelandic cooperation on reservoir modelling" (acronym Geomodel), financed under the Fund for Bilateral Relations through the European Economic Area Financial Mechanism (EEA FM) and the Norwegian Financial Mechanism (NFM) 2014-2021, programme “Environment, Energy and Climate Change.

Table of contents

1 Basic information

The calculator has been developed for users without programming skills to create such a calculation algorithm. The calculator can be helpful for scientists and engineers working in the geothermal industry. Its most significant advantage is the ability to efficiently prepare an input file in Excel. The calculator-generated results provide valuable information about the wellhead temperature change in the simulation conditions. Such data can be used to estimate the geothermal potential in a specific location or in existing geothermal heating plant. They can provide information on when the optimum wellhead temperature will be reached and hence plan the simultaneous operation of peak load sources.

2 Calculator theory

The GeoModel project focuses on the use of low-temperature geothermal resources. That is why the flow in the well is assumed to be single-phase, meaning the fluid flow in a liquid state. The rock formation is treated as a continuous, isotropic medium without internal heat sources and with constant thermophysical properties. It is assumed that there is no fluid flow within the rock formation – only heat exchange occurs and it happens under unsteady conditions. The finite difference method, i.e. an explicit scheme was used to describe temperature changes over time in the rock formation surrounding the well.

2.1 Description of the modelled area geometry

The process can be considered in cylindrical coordinates owing to the assumptions made (Figure 1).

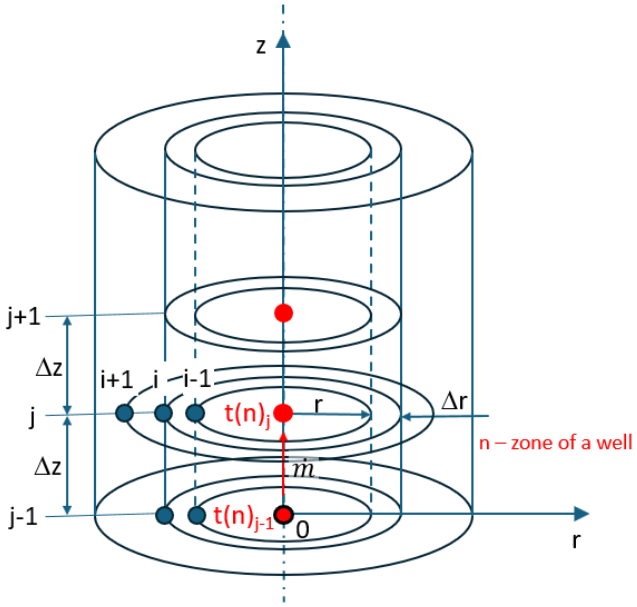

Figure 1. Well vicinity zone in cylindrical coordinates, discretisation diagram of the rock formation, and spatial location of the well

Based on the assumptions, the temperature change over time will be described by the following equation:

Equation 1

$$\frac{\partial t}{\partial \tau} = \frac{\lambda}{c\,\rho}\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial z^2}\right)$$

where:
t – temperature [K],
τ – time [s],
λ – thermal conductivity coefficient [W/(m·K)],
c – specific heat capacity[J/(kg·K)],
ρ - density [kg/m^3],
r – radius, distance form axis of symmetry of the well [m],
z – height, counted from the bottom of well [m].

One can easily notice that the adopted discretisation scheme enables accounting for various material types in each space element. This way, the well construction, including the casings diameters and materials, cement, and rock formation, can be set freely. Moreover, the rock formation properties, which may vary with depth, can also be represented for each depth interval.

3 Heat exchange

3.1 Heat exchange in the rock formation

According to the assumptions, the finite difference method (FDM) can be used to describe an unsteady heat exchange in the rock formation. It follows the rock formation space discretisation (Figure 1). By using symmetric difference quotients of the adequate order to describe the derivatives versus spatial coordinates, the differential form of Equation 1 can be written as follows (derivations and more information can be found in the literature (Wiśniewski and Wiśniewski, 1997):

Equation 2

$$\frac{t_{i,j,k+1} - t_{i,j,k}}{\Delta\tau} = \frac{\lambda}{c\,\rho}\left[\frac{\left(1 - \frac{1}{2i}\right)t_{i-1,j,k} - 2t_{i,j,k} + \left(1 + \frac{1}{2i}\right)t_{i+1,j,k}}{(\Delta r)^2} + \frac{t_{i,j-1,k} - 2t_{i,j,k} + t_{i,j+1,k}}{(\Delta z)^2}\right]$$

where:
r – radius in cylindrical coordinates [m],
z – height in cylindrical coordinates [m],
i – node number along the r coordinate (radius) [-],
j – node number along the z coordinate (height) [-],
k – time step number [-],
t – temperature [K],
λ – thermal conductivity coefficient of the rock [W/(m·K)],
c – specific heat capacity of the rock [J/(kg·K)],
ρ – rock density [kg/m^3].

The unknown in the equation above is $t_{i,j,k+1}$ - the temperature in the *i,j* node in the next time step *k+1*:

Equation 3

$$t_{i,j,k+1} = \frac{\lambda\,\Delta\tau}{c\,\rho}\left[\frac{\left(1 - \frac{1}{2i}\right)t_{i-1,j,k} - 2t_{i,j,k} + \left(1 + \frac{1}{2i}\right)t_{i+1,j,k}}{(\Delta r)^2} + \frac{t_{i,j-1,k} - 2t_{i,j,k} + t_{i,j+1,k}}{(\Delta z)^2}\right] + t_{i,j,k}$$

3.2 Initial conditions

Establishing the initial conditions is among the requirements for a unique Fourier equation solution described in cylindrical coordinates by Equation 1. The initial conditions may refer to a scenario where the well's exploitation commences after a long inactivity period. Suppose the well has been inactive long enough for the temperature field in the rock formation to return to its natural state. In that case, the initial conditions may reflect the well temperature profiling curve (temperature distribution with depth) if known. If the thermal profiling curve is not known, the initial conditions can be described according to the regional geothermal gradient. In both cases, the temperature in the computational grid nodes depends only on the depth.

Another scenario when the initial conditions should be established is when one wants to reproduce/ restore a disturbed temperature field in the rock formation caused, e.g., by previous well exploitation. In the reference case, establishing the initial conditions requires assigning temperatures to all nodes in the modelled area. This is most conveniently done by importing an input file with an appropriate data format. This will be facilitated if the program that determines the temperature distribution in the modelled space saves the temperature distribution as an output file.

3.3 Boundary conditions

Boundary conditions are another requirement for a unique solution to the unsteady heat transfer equation in the modelled area. Dirichlet boundary conditions are proposed, also known as first type boundary conditions. Their use provides significant stability of the numerical model, and their implementation in the analysed process involves temperature determination in the selected model nodes (Figure 2). It should be noted that the nodes with first type boundary conditions should be sufficiently distant from the well to prevent thermal disturbances caused by the fluid from reaching the steady temperature nodes. In practice, for the analysed process, this means setting a condition of several dozen metres (~50 m) at the cylinder boundary and several to 20 metres for the bottom. The suggested spatial extent for the model grid was estimated based on (Pająk and Bujakowski, 2000).

A dynamic first type boundary condition was applied for the subsurface zone. Determining a constant and time-invariant temperature in the subsurface zone does not reflect the actual heat exchange conditions in the surface zone near the borehole. In reality, the rock/ground temperature near the well is higher than the natural temperature. A dynamic boundary condition involved a time-constant replacement of the temperature in the subsurface zone nodes with the

temperature from the preceding layer of elements during calculation. This way, the temperature variability in the subsurface layer was accounted for, despite the application of a first type boundary condition. Test calculations confirmed the physical correctness of the results. Further calibration and confirmation of the assumption would entail confrontation with the measurement data, unavailable for the calculator code authors (the temperature values near the well, in the subsurface zone are typically not measured).

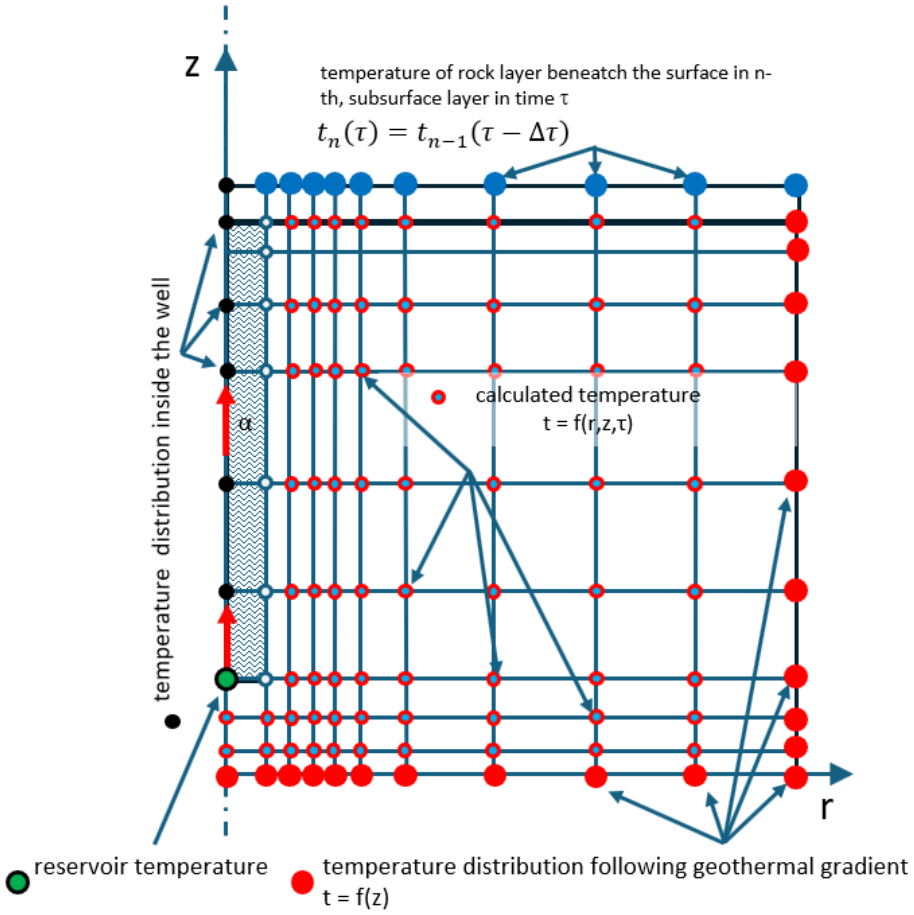

Figure 2. Suggested scheme for the determination of boundary conditions

3.4 Heat exchange between the fluid and the well's inner wall

The temperature distribution of the fluid flowing through the well can be described using the zone balance method. Assuming that mass balance is maintained in the well (the mass flow rate $\dot{m}$ remains constant throughout the exchanger), the temperature in the analysed exchanger zone n (Figure 1) changes linearly from the zone inlet temperature $t(n)_{j-1}$ to the zone outlet temperature $t(n)_j$. The power exchanged between the fluid flowing through the well and the rock formation causes a change in the fluid temperature, according to the following equation:

Equation 4

$$\boldsymbol{P(n)_{fr} = \dot{m}\, c(n)_f \left[t(n)_j - t(n)_{j-1}\right]}$$

where:
$P(n)_{fr}$ – power exchanged between the fluid in the well and the rock formation in the *n*-th zone [W],
$\dot{m}$ – mass flow rate of the fluid [kg/s],
$c(n)_f$ – specific heat capacity of the fluid [K],
$t(n)_j$ – fluid temperature at the *n-th* zone outlet [K],
$t(n)_{j-1}$ – fluid temperature at the *n-th* zone inlet [K].

The equation above can be solved iteratively by determining the fluid temperature at the *n-th* zone outlet. This method determines the fluid's specific heat capacity in the zone, which strongly contributes to fluid heating or cooling.

The heat transfer between the fluid and the geological medium is a convective heat transfer. It is described by the following equation:

Equation 5

$$\mathbf{P(n)_k = \alpha(n)_k\, F(n)\left(\overline{t_f(n)_k} - \overline{t_{wsf}(n)_{k-1}}\right)}$$

where:
$P(n)_k$ – power exchanged between the fluid and the inner surface of the well casing, in the *n*-th zone, at the *k*-th time step [W],
$\alpha(n)_k$ – coefficient of convective heat transfer between the fluid in the well and the well casing inner wall, in the *n*-th zone, at the *k*-th time step [W/(m·K)],
$F(n)$ – inner surface area of the pipe in the heat exchanger *n*-th zone [m^2],
$\overline{t_f(n)_k}$ – average fluid temperature in the heat exchanger *n*-th zone, at the *k*-th time step:

Equation 6

$$\overline{t_f(n)_k} = \frac{t_f(n)_{j,k} + t_f(n)_{j-1,k}}{2}$$

where:
$t_f(n)_{j,k}$ – fluid temperature at the *j* zone outlet, at the *k*-th time step (value determined iteratively - assumed) [K],
$t_f(n)_{j-1,k}$ – fluid temperature at the *j* zone inlet, at the *k*-th time step [K],
$\overline{t_{wsf}(n)_{k-1}}$ – mean temperature of the heat exchanger wall in the *n-th* zone, at the *k-1* time step (previous time step) [K]:

Equation 7

$$\overline{t_{wsf}(n)_{j,k-1}} = \frac{t_{wsf}(n)_{j,k-1} + t_{wsf}(n)_{j-1,k-1}}{2}$$

where:
$t_{wsf}(n)_{j,k-1}$ – inner wall temperature of the well at the end of the *n-th* zone in the previous time step (*k-1*) [K],
$t_{wsf}(n)_{j-1,k-1}$ – inner wall temperature of the well at the beginning of the *n-th* zone in the previous time step (*k-1*) [K].
The value of the $t_{wsf}(n)_k$ temperature on the inner surface of the pipe wall in the *n-th* zone, at the *j* height at the current *k-th* time (time step), can be determined using the following equation:

Equation 8

$$\boldsymbol{t_{wsf}(n)_{j,k} = t_f(n)_{j,k} - \frac{P(n)_k}{\alpha(n)_k F(n)}}$$

The coefficient of convective heat transfer can be determined using the Nusselt number (Nu):

Equation 9

$$\mathrm{Nu} = \frac{\alpha\, d}{\lambda}$$

where:
Nu – Nusselt criterion number [-],
a – coefficient of convective heat transfer of the fluid [W/(m^2·K)],
d – characteristic dimension [m],
λ – fluid's thermal conductivity coefficient [W/(m·K)].

In the case of laminar flow (Reynolds number < 2000) in a pipe, the coefficient of convective heat transfer can be calculated using Equation 10 (Wiśniewski and Wiśniewski, 1997):

Equation 10

$$\boldsymbol{\frac{\alpha\, d}{\lambda} = 0.15\, Re^{0.33} Gr^{0.1} Pr^{0.43} \left(\frac{Pr}{Pr_{wsf}}\right)^{0.25} \varepsilon}$$

where:
Re, Gr, Pr – Reynolds, Grashof and Prandtl number for the fluid [-]:
$Re = \frac{w\, l}{\nu}$, $Gr = \frac{g\, l^3}{\nu^2}\beta\Delta t$, $Pr = \frac{\nu}{a}$,
w – fluid velocity [m/s],
l – characteristic dimension [m],
a – temperature equalisation coefficient $\frac{\lambda}{c \cdot \rho}$ [m^2/s],
g – gravitational acceleration [m/s^2],
β – volumetric thermal expansion of the fluid [1/K],
Δt – temperature difference between the fluid and the heat exchange surface [K],
ν - kinematic viscosity coefficient [m^2/s],
Pr_{wsf} – Prandtl number of the fluid at the wall temperature $\overline{t_{wsf}(n)_k}$ [-],

ε - coefficient representing the ratio of the pipe length l to its diameter d [-]; for geothermal wells l/d > 50, therefore ε =1. In other cases, refer to the literature (Wiśniewski and Wiśniewski, 1997) (page 246, Table 6.3).
In the case of turbulent flows (Re > 2000), for water and other low-viscosity fluids (1 < Pr < 20), the empirical relationship (Wiśniewski and Wiśniewski, 1997) can be used:

Equation 11

$$\boldsymbol{Nu = 0.0155\, Re^{0.83} Pr^{0.5}}$$

4 Determination of exploited fluid properties

In the case of wells where geothermal fluid is extracted, the fluid can be expected to be brine rather than pure water. From the perspective of modelling fluid parameters in a geothermal well, mineralisation affects the fluid's specific heat capacity, density, and viscosity. The fluid thermophysical properties, accounting for mineralisation, can be determined based on the literature data. Proposed equations for brine properties are available on the Project website (IGSMiE PAN, 2024).

5 Flow resistance

The pressure distribution within the well can be determined by calculating the flow resistance of the geothermal fluid through each *n-th* zone of the well Δp(n) (Recknagel, Sprenger, Hönmann, and Schramek, 1994):

Equation 12

$$\boldsymbol{\Delta p(n) = \varphi \frac{\sigma\, w^2 \rho\, L(n)}{2d}}$$

where:
Δp(n) – flow resistance in the *n-th* zone of the well [Pa],
φ – dimensionless roughness coefficient of the pipe wall typically takes the following values:
1 – for smooth, new pipes made of steel, copper, or brass,
1.1 – for new cast iron pipes,
1.56 – for cast iron and riveted steel,
1.78 – for old steel pipes (this value can be considered typical for drill pipes),
2.22 – for old riveted steel pipes,
σ - coefficient of flow resistance non-linearity:

$$\sigma = \begin{cases} \text{jeżeli Re} < 3000 -\!\!\blacktriangleright \dfrac{64}{\text{Re}} \\ \text{jeżeli } 3000 \le \text{Re} \le 10000 -\!\!\blacktriangleright \dfrac{0.3164}{\text{Re}^{0.25}} \\ \text{jeżeli R} > 10^4 -\!\!\blacktriangleright \dfrac{0.221}{\text{Re}^{0.237}} + 0.0032 \end{cases}$$

Π – number Pi [-],

d – diameter [m],
μ – coefficient of the fluid's dynamic viscosity [Pa·s],
w – fluid flow velocity [m/s],
ρ – fluid density [kg/m^3],
L(n) – length of the *n-th* zone where the fluid flow occurs [m].

The total water pressure at the end of the well's *n-th* zone, at the *k-th* time step, is determined by the following relationship:

Equation 13

$$\boldsymbol{p_c(n)_{j,k} = p_c(n)_{j-1,k} - \Delta p(n)_k}$$

The fluid's static pressure at the *n-th* zone outlet *n*, at the *k-th* time step amounts to $(n)_{j,k}$ – depending on fluid parameters such as viscosity, density, specific heat capacity, etc. It is determined by subtracting the dynamic pressure, hydrostatic pressure drop $\Delta p_s(n)_k$ and the flow resistance $\Delta p(n)_k$ from the total pressure at the beginning of the zone $p_c(n)_{j-1,k}$:

Equation 14

$$\boldsymbol{p_s(n)_{j,k} = p_c(n)_{j-1,k} - \Delta p(n)_k - \frac{1}{2}\overline{\rho(n)_k}(w(n)_k)^2 - g\, h(n)\, \overline{\rho(n)_k}}$$

where:
$p_s(n)_{j,k}$ – fluid static pressure at the *k-th* time step, at the *n-th* zone outlet [Pa],
$p_c(n)_{j-1,k}$ – fluid total pressure at the *k-th* time step, at the *n-th* zone inlet [Pa],
$\Delta p(n)_k$ – pressure drop in the *n-th* zone, at the *k-th* time step, due to flow resistance [Pa],
$\overline{\rho(n)_k}$– fluid average density in the *n-th* zone, at the *k-th* time step [kg/m^3],
$w(n)_k$ – fluid flow velocity in the *n-th* zone, at the *k-th* time step [m/s],
g – gravitational acceleration [m/s^2],
h(n) – *n-th* zone height [m].

6 Setting up the environment

The programme input data are prepared as an Excel file. The programme code was written in `Python` version `3.11.7`. In addition to Python, libraries such as `CoolProp 6.6.0`, `Pandas 2.1.4`, `NumPy 1.26.2`, and `Matplotlib 3.7.1`., `Numba 0.60,` required for calculations shall be installed. Aforementioned versions of the libraries were used in the development of the program. However, newer releases should also work correctly when using `pip` or `conda` package managers, whose role includes ensuring the proper compatibility of installed packages.

7 Algorithm description

The calculator consists of four modules where the appropriate computational procedures have been defined, along with the main file, `main.py`. The module called `brine_prop.py` contains

defined functions that determine the thermodynamic properties of brine, such as specific heat capacity, density, compressibility, dynamic viscosity, thermal conductivity, and coefficient of convective heat transfer. Based on the reference literature review, these properties are defined as functions dependent on temperature, pressure, and mineralisation. The `fdm.py` module includes a computational procedure that uses the finite difference method (FDM) in a cylindrical space (2D). The procedure is designed for an asymmetric grid. This library defines the relevant first-order and second-order partial derivatives, along with the unsteady state. The *`wells.py`* module contains a set of predefined functions mainly responsible for processes inside the well casing and its direct vicinity. The *`major_lib.py`* module is the most extensive for the number of functions included. Some of these functions are created to execution of other functions. Still, the functions determining energy propagation in the rock formation surrounding the well and generating the relevant plots are the most important part of the module. The *`main.py`* module, which contains the most important procedures triggered sequentially, is the calculator's key file. It also supports input data uploading and then generates the output files.

A user with no basic Python knowledge, must only fill in an Excel worksheets to perform the simulation. A user with basic programming skills can edit the program code according to their needs.

7.1 Input file

To perform the simulation, an Excel file (`.xlsx`) shall be generated and shared in the main folder along with the calculator files in a Python file (`.py`). The file should be dedicated to a production well (`well_prod_input.xlsx`) or an injection well (`well_inj_input.xlsx`), depending on the user-required type of simulation. The procedure for filling out the input data for a production well is presented below. Each input file contains four worksheets, where the user needs to enter the required data. The first worksheet, named `geo`, defines the well structure and geological formation (Figure 3).

	A	B	C	D	E	F	G	H	I
1	h1[m]	h2[m]	t1[°C]	t2[°C]	d1[m]	mat	d2[m]	mat	D[m]
2	0	1	8		0.2445	3	0.3	3	6
3	1	50			0.2445	3	0.3	3	6
4	50	100			0.2445	3	0.3	3	6
5	100	250			0.2445	3	0.3	3	6
6	250	750			0.2445	3	0.3	3	6
7	750	2000		60	0.2445	3	0.3	3	6

Figure 1 View of the input file parameters in the `geo` sheet

The depth of individual model layers is defined in meters using the columns with headers h1 and h2. The physical units entered into and required in the spreadsheet are specified in square brackets in the table header line. When a successive model layer is added, its starting depth shall match the ending depth of the previous one (as shown in Figure 3).

In the following columns, the temperature distribution is entered. If temperatures at specific depths are known, they can be entered directly into the corresponding cells. One should remember that the temperature at the bottom of one layer is the same as the temperature at the top of the next layer, similar to depth values. If the layer temperatures are unknown, provide only the `t1`temperature at the top of the first layer and the temperature at the bottom of the deepest layer (as shown in Figure 3). In this case, the program will automatically estimate the remaining temperatures using the approximate geothermal temperature gradient. The dimensions that characterise the modelled area in the horizontal plane are defined in the following columns. The input file uses diameters, but the calculator uses zone radii due to the assumed symmetry of the area around the well. The diameters used in the input file include `d1`, `d2`, and `D`. The `d1` value is the inner diameter of the well casing, representing the area filled with brine by default. The area between `d1` and `d2` is an equivalent near-well zone, including casing materials, cement, and steel components. The program calculates an equivalent material coefficient for this zone specified in the `mat` column. Only the rock formation between `d2` and `D` is found in the last zone. Diameter `D` defines the maximum modelled area and the maximum radius. The next worksheet, named `mat`, contains material properties, including thermal conductivity, specific heat capacity, and density of the materials used in defining the model (Figure 4).

	A	B	C	D	E	F	G	H	I	J	K
1	mat	λ[W/(mK)]	c[J/(kgK)]	r(kg/m3]	type	warinnigs					
2	0	0.6	4190	1000	water	User can not change the number of matarial in the case of water, it is always 0					
3	1	5.00	2000.00	3000.00	air	User can not change the number of matarial in the case of air, it is always 1					
4	2	4.50	1100.00	2600.00	well surroundings						
5	3	4.50	1100.00	2600.00	rocks 1						

Figure 2 View of parameters in the input file in `mat` sheet

The model distinguishes the materials with numbers assigned to them in the first column. The values are assigned upon defining the model structure in the `geo` worksheet. The equivalent

coefficients corresponding to the construction materials in the near-well zone, i.e., the casing material, cement, potential steel components, etc., should be included in the material `well surrounding`. These coefficients should be estimated depending on the well construction or left as the default values provided by the authors. The `work` sheet defines the well's operating scheme (Figure 5).

	A	B	C	D
1	time_[s]	flow_[kg/s]	t_[°C]	pBot[Pa]
2	7200	5	60	20601000
3	14400	10	60	20601000
4	21600	15	60	20601000
5	25200	20	60	20601000

Figure 3 View of the input file parameters in the *work* sheet

This worksheet identifies the simulation time, geothermal fluid flow rate, and reservoir temperature. The initial pressure at the well bottom is also specified (e.g., hydrostatic pressure). The well operating scheme can be defined in two ways. The first method assumes constant well operation in the set conditions over the entire simulation period (a single data line). The second method (shown in Figure 5) involves adding successive lines as needed and defining various well simulation parameters. This enables an analysis of the well behaviour at a variable flow rate over time. One should note that the time value in the each following lines represents the total cumulative simulation time. When successive working phases are added, the well will operate at a specific output for the time calculated as the difference between the next and previous lines. If an injection well is simulated, the numerical value in the `flow` column (`work` worksheet) must be preceded by a minus sign. This is the information for the algorithm that the fluid flow inside the well occurs in the opposite direction. The final worksheet, called `others`, contains additional simulation parameters, such as geothermal water mineralisation, pipe roughness, iteration accuracy, maximum node spacing along the depth, and the maximum allowed time step (Figure 6).

	A	B
1	description	value
2	brine TDS [kg_TDS/kg_pureWater]	0.05
3	the well pipes roughness [-]	1.78
4	Iterative accuracy (suggested 1E-5)	1.00E-05
5	maximal allowed length of a section by Z [m]	30
6	maximal alllowed value of time step [s]	40

Figure 4 View of the input file parameters in the `others` sheet

The user can freely modify the data. The worksheets describe all parameter units. The user can also change the type of pipes used in the simulation by adjusting the wall roughness factors according to the values provided in Table 1.

Table 1 Possible values of the wall roughness factor

Pipe type	Pipe wall roughness factor
Smooth, new pipes made of steel, copper, or brass	1.00
New cast iron pipes	1.10
Cast iron and riveted steel pipes	1.56
Old steel pipes (this value can be considered typical for drill pipes).	1.78
Old riveted steel pipes.	2.22

7.2 Calculator script

Before starting the simulation, the user must set the parameter in the main calculator file to specify the simulated well type. Defining the well type in the code is very simple:

- `1` represents a production well,
- `0` represents an injection well.

To set the well type, change the value in the first if statement in the `main.py` file (Figure 7).

```
4   def main():
5
6
7       if 1:
8           fileName = 'well_prd.xlsx'
9       else:
10          fileName ='well_inj.xlsx'
11
```

Figure 5 Determination of the simulated well type – a production well (number 1) in this case

In the final part of the script, data generation for an Excel file is defined by default. A user knowing how to modify the calculator source code can adjust the output data to their needs.

7.3 Simulation run

The calculator simulation time depends on several factors. First, the actual simulation time will be longer if the analysed model consists of many layers composed of different materials. The well depth will contribute to the number of nodes where calculations are performed. The total assumed simulation time also impacts the computation time. During the calculations, the code editor terminal (Figure 8) displays the information about the simulation progress (percentage of simulation time lapsed), the actual time step, the current geothermal fluid temperature in the reservoir, and the wellhead temperature.

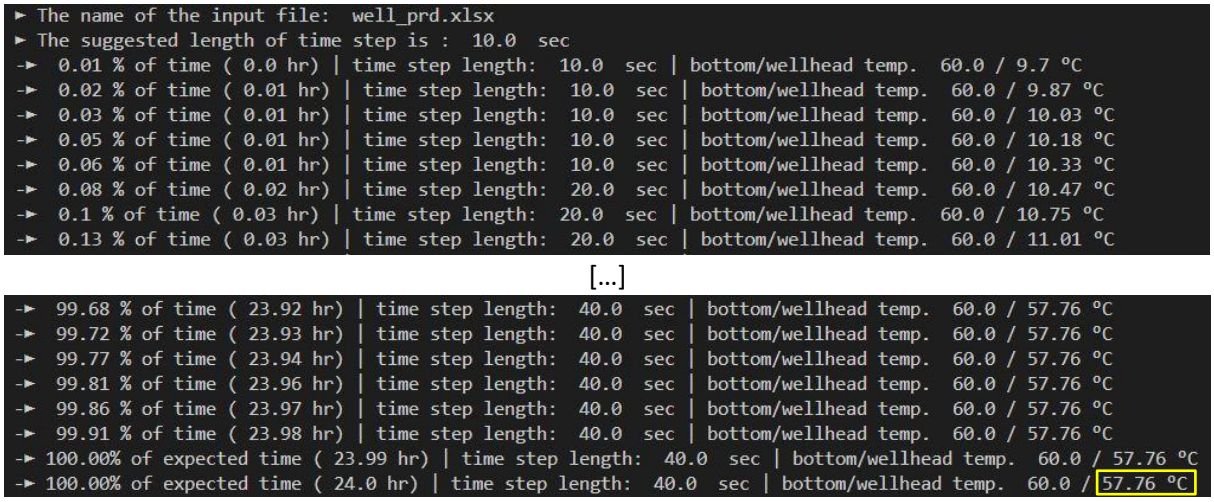

Figure 6 View of the calculator simulation screen

7.4 Output file

After the simulation is completed, an *out.xlsx* file is generated in the main folder. This file contains essential data regarding the temperature distribution in all model nodes after reaching the last simulated time step (Figure 9).

	A	B	C	D
1	Radius R [m]	Depth Z [m]	T_init [°C]	T_end [°C]
2	0	0	8	55.46448
3	0	1	8.026	55.46448
4	0	50	9.3	55.70501
5	0	80	10.08	55.84129
6	0	110	10.86	55.97519
7	0	140	11.64	56.10676
8	0	170	12.42	56.23601

Figure 7 View of output data generated in the Excel file

The file contains the simulation node coordinates (`R, Z`), and the initial (`T_init`) and final temperature (`T_end`) values for those coordinates. Additionally, four graphs are generated and displayed simultaneously (Figures 10-13).

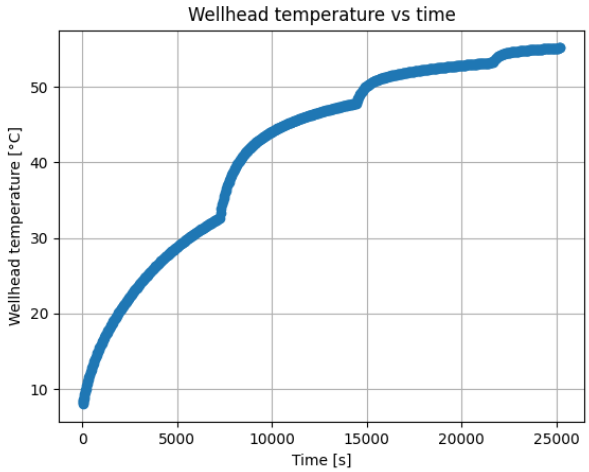

Figure 8 Wellhead temperature during simulation

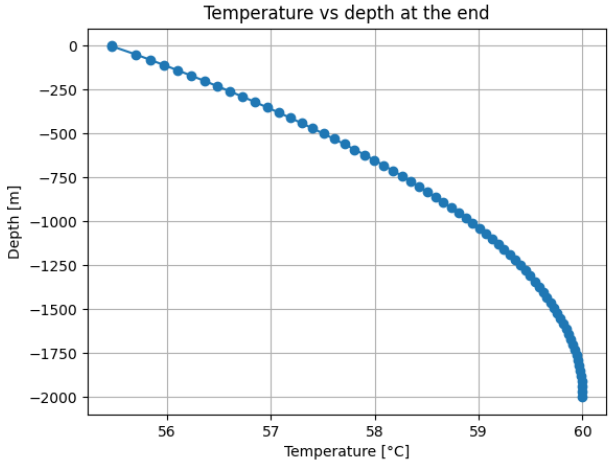

Figure 9 Rock formation temperature as a function of depth for the last time step

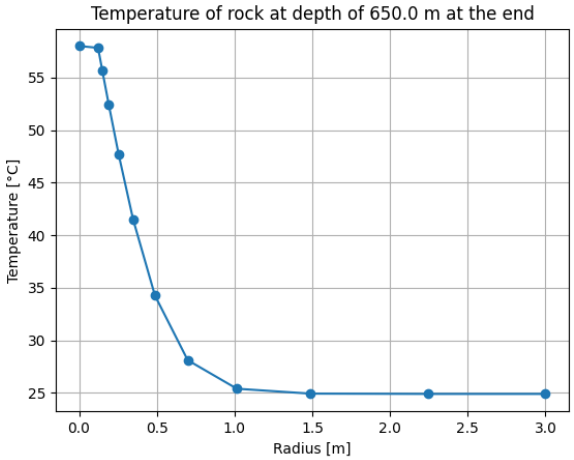

Figure 10 Rock formation temperature at the set depth at the end of the simulation time

– a change in the depth level is only possible within the code

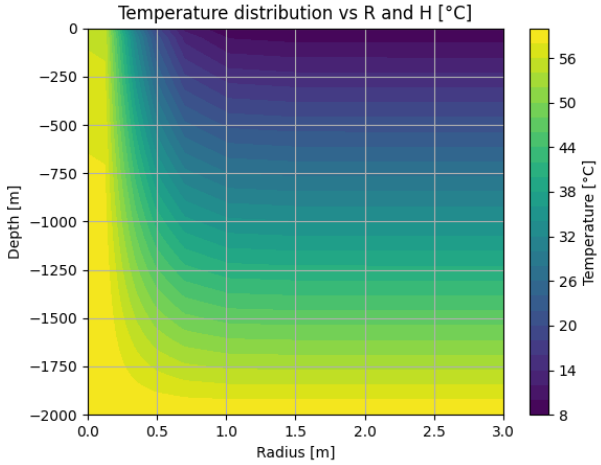

Figure 11 Temperature distribution vs the analysed model's radius and depth

If an injection well is simulated, an additional graph showing the wellhead pressure over the entire injection simulation period is generated.

8 Limitations

To make the calculator more user-friendly, a number of simplifications, mentioned earlier, have been made. The calculator is designed for single-phase flows. Therefore, it will not be useful for conditions where the geothermal fluid is in the form of steam or a mixture of liquid and gas. Another limitation of the calculator is that it allows the simulation of only a single well. This means that it is not possible to simultaneously simulate both a production and an injection well. One of the major limitations is also the computation time, which can increase significantly depending on the size of the computational grid and other simulation parameters.

9 Summary

The program helps users simulate the wellhead parameters without requiring programming skills. All crucial input parameters are entered in the Excel file sheets. The tool is so versatile that, in addition to its essential functions, it can be adapted for other tasks in the future. It features an open-source code and is free of charge. The calculator can work as a standalone tool or be a supplement to other more advanced programs or be used to verify results. Owing to its versatility, the users can simulate the operating conditions of production and injection wells. The calculator stands out with its reliance on a dedicated created module of brine thermophysical properties depending on the values of temperature, pressure, and mineralisation over a wide range.

10 Literature

Dygulska, A. and Perlańska, E. (2015). *Mapa wietrzności Polski.* Słupsk: Akademickie Centrum CzystejEnergii (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/

https://kierunkizamawiane.upsl.edu.pl/pliki/czystaenergia/raport2_II.pdf).

MEERI PAS. (15 March 2024). *Geomodel*. Downloaded from Parametry termofizyczne wody zasolonej: https://geomodel.pl/parametry-termofizyczne-wody-zasolonej/

Pająk, L. and Bujakowski, W. (2000). *Efektywność wykorzystania głębokich odwiertów wiertniczych jako wymienników ciepła wykorzystujących energię geotermiczną.* Kraków: Wydawnictwo Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk.

Recknagel, H., Sprenger, E., Honmann, W. and Schramek, E. R. (1994). *Poradnik Ogrzewanie i Klimatyzacja z uwzględnieniem chłodnictwa i zaopatrzenia w ciepłą wodę.* Gdańsk: EWFE - Revision 1.

Wiśniewski, S. i Wiśniewski, T. S. (1997). *Wymiana ciepła.* Warsaw: Wydawnictwa Naukowe i Techniczne.

Thermophysical properties of brines

Driesner, T. and Heinrich, C.A. [2007] Part I: Correlation formulae for phase relations in temperature–pressure–composition space from 0 to 1000°C, 0 to 5000bar, and 0 to 1 X-NaCl. *Geochimica et Cosmochimica Acta,* 71(20), 4880–4901. (density, specific heat)

Driesner, T. [2007] Part II: Correlations for molar volume, enthalpy, and isobaric heat capacity from 0 to 1000 °C, 1 to 5000 bar, and 0 to 1 X-NaCl. *Geochimica et Cosmochimica Acta,* 71(20), 4902–4919. (density, specific heat)

Mao, S., Duan, Z., [2009] The viscosity of aqueous alkali-chloride solutions up to 623K, 1,000bar, and high ionic strength. *International Journal of Thermophysics,* 30, 1510–1523. (dynamic viscosity)

Qasem, N.A.A. Generous, M.M. Qureshi, B.A. and Zubair, S.M. [2021] A Comprehensive Review of Saline Water Correlations and Data: Part II—Thermophysical Properties. *Arabian Journal for Science and Engineering,* 46, 1941–1979. (heat conduction coefficients)

Batzle, M. and Wang, Z. [1992]. Seismic properties of pore fluids. Geophysics VOL. 57, NO. 11.