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Elimination of the Thermal Lift Effect from Pumping Observations in Deep Geothermal Wells

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ABSTRACT

During the pumping of geothermal wells, water at the wellhead may reach a temperature close to the bottomhole conditions, especially when the flow rate is high and the pumping time is long enough. As a result of flow, the mean temperature of the fluid in the well rises, causing the average density of fluid to decrease. The volumetric expansion of water due to temperature rise - called the thermal lift effect - often disturbs the readings of the wellhead pressure or the water level. It often happens that in the case of deep wells with good filtration parameters of the aquifer, the shape of the drawdown curve is far from expectations, because the effect of water expansions masks the true drawdown. In any case, the thermal lift effect always causes the drawdown to be smaller than it would be observed if there was no volumetric expansion of water. This in turn can lead to overestimation of resources and unsustainable exploitation. Therefore, it is good practice to separate the thermal lift effect from the raw data when interpreting both short- and long-term pumping data. This allows to filter out noise, correctly assess the actual drawdown, and as a result - the correct transmissivity of the aquifer. As part of the GeoModel project, THERMALIFT package was developed. This Python tool allows for the correction of raw pumping data and graphical representation of results on graphs. The tool was designed to work with liquid-only wells for both freshwaters and brines.

1. INTRODUCTION

In documenting geothermal water resources, it is important to properly determine the filtration parameters, mainly reservoir transmissivity. Its calculation is based on the results of pumping tests or short term production. This is the most reliable method to date for determining the filtration properties of an aquifer. Geothermal waters usually occur at great depths, where there is high temperature and pressure, therefore, these factors cause a number of interpretation difficulties. They are related, among others, to the non-isothermal flow of water in the borehole, variation of flow rate and wellhead temperature during pumping and the release of gases dissolved in water as a result of the pressure dropping below the saturation pressure. In this article, the authors address the issue of the influence of wellhead temperature variations during pumping on the recorded water level or wellhead pressure. This phenomenon is called thermal lift effect.

It often happens that in the case of deep wells with good filtration parameters of the aquifer, the shape of the drawdown curve is far from expectations, because the effect of water expansions masks the true drawdown. The deeper the well and the higher the bottomhole temperature, the more significant this effect is. In any case, the thermal lift effect always causes the drawdown to be smaller than it would be observed if there was no volumetric expansion of water. This in turn can lead to overestimation of resources and unsustainable exploitation, because the real drawdown is often miscalculated. One way to get rid of this problem is to measure the water level (or the wellhead pressure) in observation wells. Another way is to measure the bottomhole pressure. Unfortunately, both of these solutions are rarely available, especially in low- and medium-temperature sedimentary systems. It is usually simply too expensive to drill observation wells 2–3 km deep or conduct long-term bottomhole pressure monitoring. However, it is not only a good practice, but sometimes a necessity, to separate the thermal lift effect from the raw data when interpreting both short- and long-term pumping data. This allows to filter out noise, correctly assess the actual drawdown, and as a result - the correct transmissivity of the aquifer.

The thermal lift effect, to the authors' knowledge, was first mathematically described in the literature in the mid-1990s by Kawecki (1994, 1995). Later, application of his approach was applied to geothermal wells in sedimentary formations in Poland, proving its usefulness in interpreting hydrodynamic tests and long-term historical data (Bielec & Miecznik 2012, Miecznik 2017). However, for all these years there was no tool that would automate the calculations and allow for a graphical comparison of the water level before and after thermal lift correction. The opportunity to develop and publicly share such a tool appeared with the start of the GeoModel project (www.geomodel.pl/en), in which Polish and Icelandic specialists decided to develop a set of Python scripts to support the work of geothermal reservoir engineers. THERMALIFT is a Python package that allows for the correction of raw pumping data and graphical representation of results on graphs. The only input data required are temperature and water level or wellhead pressure during pumping and the temperature profile along the well under natural conditions.

2. THEORY OF THERMAL LIFT

Below formulation is valid for both vertical and deviated wells with conduction as a dominant heat transfer process in the formation. These are typical conditions for majority of sedimentary formations. Figure 1 shows the temperature profile in the well in static (natural) conditions and during pumping. Under static conditions, the temperature profile along the well is the same as the temperature distribution in the rock formation. During pumping, well is gradually heated. The temperature at the wellhead is closer to the bottomhole temperature the longer the production takes or the higher the flow rate of the pumped liquid.

The hydrostatic pressure exerted by the water column is:

$$p = g\int_0^{H_{MD}} \rho_w(z)dz \quad (1)$$

where p **-** hydrostatic pressure, g **-** Earth's gravitational acceleration, ρ_w - the density of the water column in the borehole, H_{MD} – measured depth of the borehole, z - integration variable (depth).

Since the pressure exerted at the bottom of the well is independent of the temperature of the liquid inside it, the multiplication of the height of the water column and its density will be the same for the static and operating well:

$$H_d\overline{\rho_w^d} = H_s\overline{\rho_w^s} \quad (2)$$

where H_d - height of the water column in dynamic conditions, H_s - height of the water column in static conditions, $\overline{\rho_w^d}$ - average density of the water column under dynamic conditions, $\overline{\rho_w^s}$ - average density of the water column under static conditions.

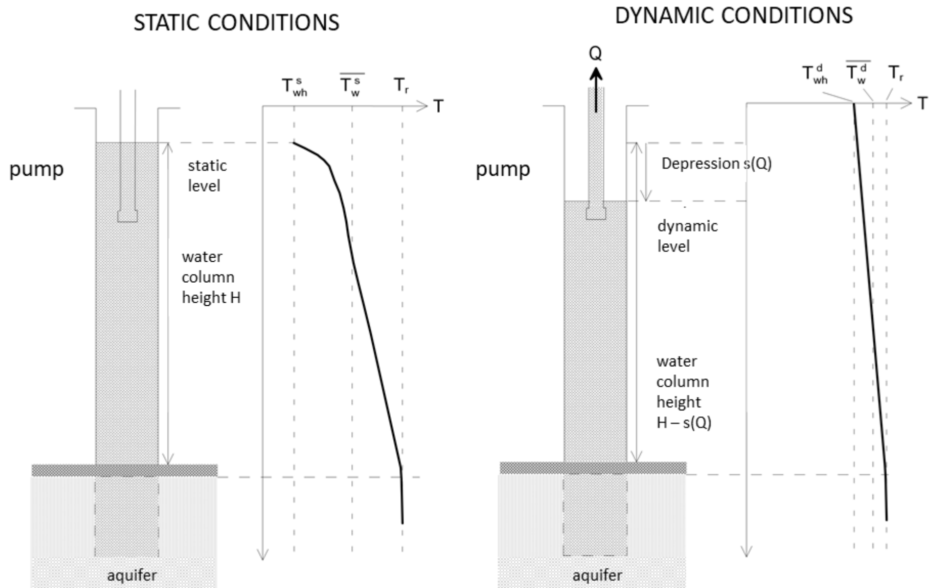

Figure 1: Diagram showing the temperature profile in the well under static and dynamic conditions (adopted from Kawecki 1995)

The average density of water in the well is as follows:

$$\overline{\rho_w} = \frac{1}{H_{MD}}\int_0^{H_{MD}} \rho_w dz \quad (3)$$

Although in general the density of water is a non-linear function of temperature, in the temperature range from 40 to 95°C (typical temperatures of geothermal water in liquid systems) the approximation by a linear function can be considered sufficiently accurate. By omitting some transformations of Equation 3 which are provided by Kawecki (1995), one obtains a relation which says that the average density of the water column is the density of water for the average (weighted) temperature of the water column:

$$\overline{\rho_w} = \rho_w(\overline{T_w}) \quad (4)$$

By inserting equation 4 into equation 2, the following relation is obtained:

$$H_d\rho_w\left(\overline{T_w^d}\right) = H_s\rho_w\left(\overline{T_w^s}\right) \quad (5)$$

where $\overline{T_w^d}$ - average water column temperature under dynamic conditions, $\overline{T_w^s}$ - average water column temperature under static conditions.

The pressure measured at the bottom of the well under static conditions is as follows:

$$p_{r,0} = \rho_w\left(\overline{T_w^s}\right) H_{MD} g + p_{wh,0} \tag{6}$$

where $p_{r,0}$ - pressure at the bottom of the well under static conditions (no extraction), $p_{wh,0}$ - wellhead pressure under static conditions.

The bottomhole pressure during operation can be expressed in the form of equation 7, which is analogous to equation 6:

$$p_r = \rho_w\left(\overline{T_w^d}\right) H_{MD} g + p_{wh} \tag{7}$$

where p_r - bottomhole pressure under dynamic conditions, p_{wh} - wellhead pressure under dynamic conditions.

The value of the water drawdown $s\left(\overline{T_w^s}\right)$ in a well is the difference between the static and dynamic bottomhole pressures:

$$s\left(\overline{T_w^s}\right) = \frac{p_{r,0} - p_r}{\rho_w\left(\overline{T_w^s}\right) g} \tag{8}$$

By substituting equations 6 and 7 into equation 8, one obtains a formula that allows to calculate the actual depression excluding the influence of the thermal lift, knowing only the static and dynamic wellhead pressure and the average water column temperature under static and dynamic conditions:

$$s\left(\overline{T_w^s}\right) = \frac{p_{wh,0} - p_{wh}}{\rho_w\left(\overline{T_w^s}\right) g} + \left[1 - \frac{\rho_w\left(\overline{T_w^d}\right)}{\rho_w\left(\overline{T_w^s}\right)}\right] H_{MD} \tag{9}$$

Subtracting the actual depression value $s\left(\overline{T_w^s}\right)$ from the static wellhead pressure, taking into account the thermal lift effect during extraction, the so-called reduced wellhead pressure value p_{wh}^{red} is obtained:

$$p_{wh}^{red} = p_{wh,0} - s\left(\overline{T_w^s}\right) \cdot \rho_w\left(\overline{T_w^s}\right) \cdot g = p_{wh} - \left[1 - \frac{\rho_w\left(\overline{T_w^d}\right)}{\rho_w\left(\overline{T_w^s}\right)}\right] \rho_w\left(\overline{T_w^s}\right) H_{MD} g \tag{10}$$

In case of the non-artesian well, following formulas are applicable. Having a pressure sensor in the submersible pump, the water level below the ground level h_m is given by equation 11:

$$h_m = h_{pump} - \frac{p - p_{atm}}{g \cdot \rho_w} \tag{11}$$

where h_{pump} - depth of the pressure sensor, p - pressure measured by the pressure sensor, p_{atm} - atmospheric pressure of 101325 Pa, g - Earth's gravitational acceleration, ρ_w - average density of the water column above the pressure sensor.

By analogy with equation 10, the reduced water level h_{red} in the production well is:

$$h_{red} = h_m + \left(1 - \frac{\rho_w(\overline{T_w^d})}{\rho_w(\overline{T_w^s})}\right) \cdot H_{MD} \tag{12}$$

Hence, the true drawdown s_{red} in the aquifer is:

$$s_{red} = h_{red} - h_{red,\ min} \tag{13}$$

where $h_{red,\ min}$ is the water level (b.g.l.) at the closed wellhead.

3. PRACTICAL APPLICATION OF THERMALIFT CALCULATOR

Thermalift calculator consists of 2 modules: brine_density.py and classes.py. The first module contains function to calculate brine density, based on the formula presented by Sun et al. (2008). The claimed accuracy is 0.1% for brine water temperature between 0 and 180°C and salinity up to 0.16 kg/kg.

The second module, classes.py contains:

- class Formation: to interpolate temperature profile in the static well in case of missing data points, in order to calculate the average formation temperature and therefore the average density of the water column in non-flowing well;
- class Well: creates an object to which several functions must be applied in a specified order to calculate the reduced wellhead pressure or water level. This class graphs contains procedures for drawing different types of charts, allowing comparison of a dataset before and after subtraction of the thermal lift.

The package also includes a sample script with data from 21 months of geothermal system operation in northwestern Poland. The script presents a step-by-step process, starting with loading the data, removing erroneous records, correcting time stamps, and then applying individual functions from both classes. Figure 2 shows the effect of using Thermalift calculator on one the available graphs with marked points 1, 2 and 3 for special attention.

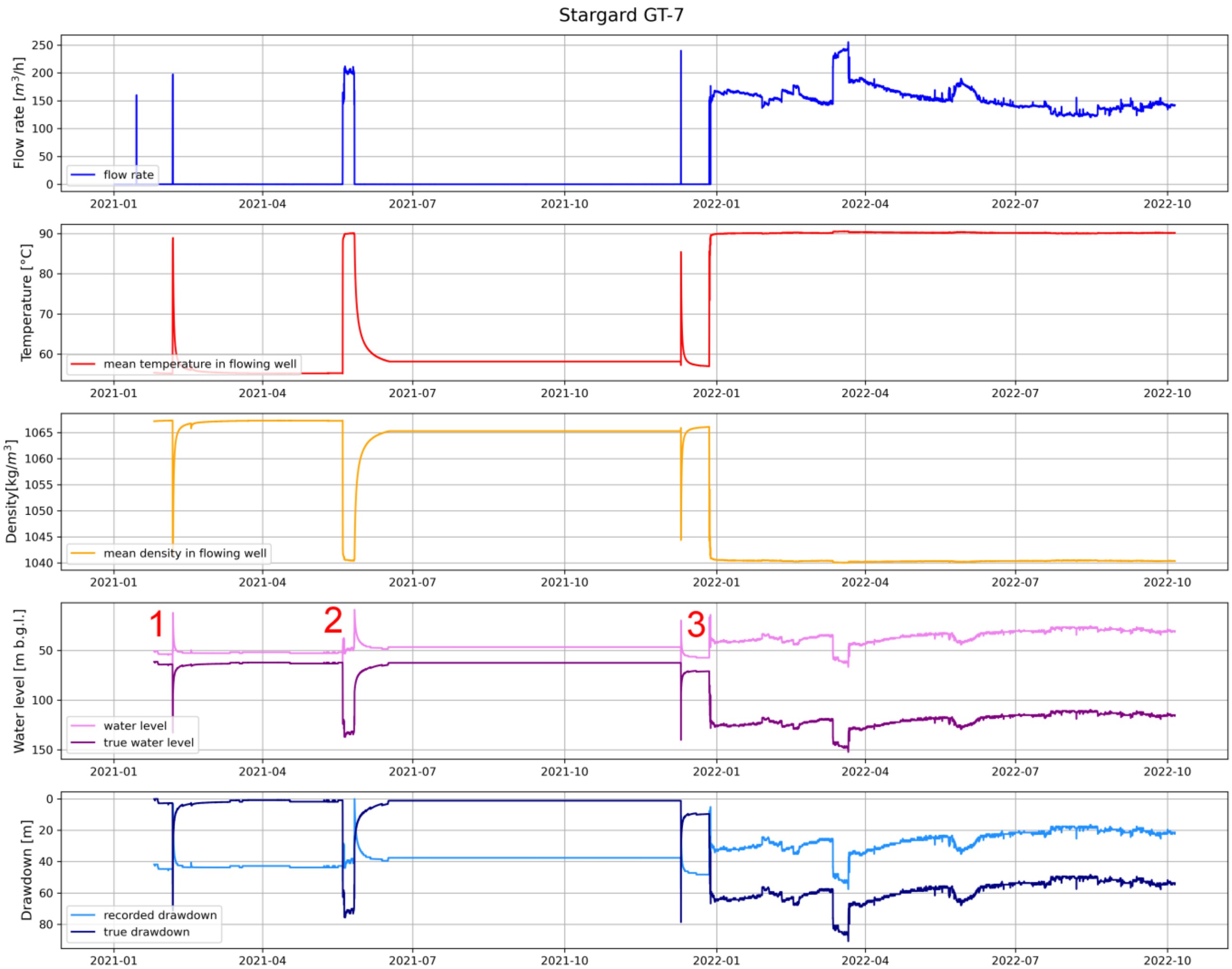

Figure 2: Effect of applying Thermalift calculator to exemplary dataset from sedimentary reservoir in Poland.

Points 1 and 2: short-term production and then closing of the wellhead. During this time, there was a rapid increase in the average water temperature in the well, as a result of which instead of the expected drawdown of the water level, the observer records a rise in the water table. This is of course caused by a rapid increase in the volume of water due to thermal expansion. After closing the wellhead, instead of the expected buildup of the water table, a drop in the water level is recorded as a result of thermal contraction.

Point 3: similarly to points 1 and 2, large fluctuations in the average temperature in the production well are causing fluctuations in the water level. As a result of this phenomenon, a much higher water table is recorded, and thus a lower drawdown than would result from the true filtration parameters of the aquifer. The application of the thermal lift correction allows not only to correct the true pressure/water drawdown, but also to assess the well efficiency by fitting a 2nd degree polynomial to the p(q) or s(q) dependence. In this way, it is possible to determine which pressure losses are related to flow resistance in the reservoir, and which to turbulent flow in the borehole and the zone near the borehole (Fig 3). This in turn allows, for example, to perform a much more accurate calibration of the 3D numerical model of the reservoir by disregarding the turbulent pressure losses.

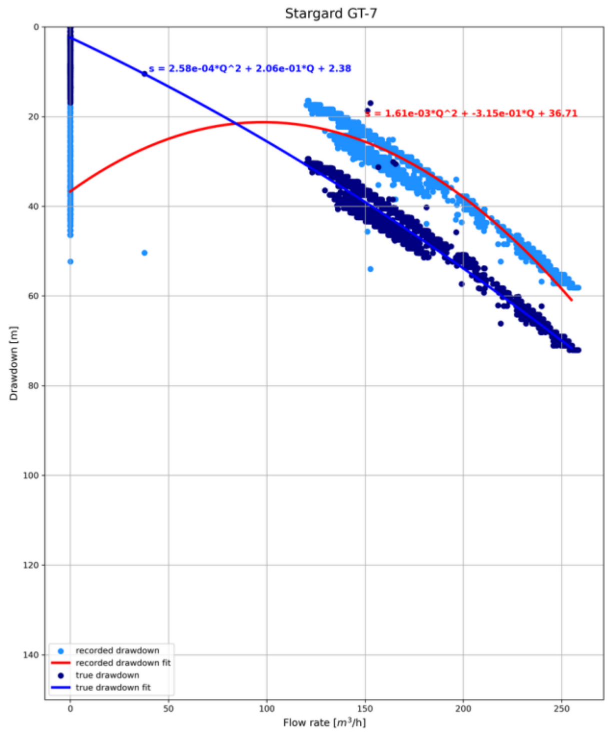

Figure 3: Effect of applying Thermalift calculator to estimate the actual flow resistance in the reservoir and in the well.

4. CONCLUSIONS

THERMALIFT is an easy-to-use, open-source Python code whose primary purpose is to assist in the interpretation of pumping tests in deep geothermal wells. Thanks to it, one can easily eliminate noise from pumping tests or the long-term historic data caused by fluctuations in the density of water in the well.

Corrected data can be later used in well test analysis to assess the actual parameters of the aquifer, such as transmissivity or filtration coefficient. This in turn allows for better calibration of numerical models. The tool requires some knowledge of Python, but this mainly concerns the data loading and possible elimination of erroneous records. Thermalift is applicable to both vertical and directional wells, but it is not necessary to know the exact trajectory of the well, but only the temperature distribution in the natural state along the borehole. The tool can be used for boreholes exploiting liquid water (not steam) with a salinity of up to 16%. Thermalift calculator should be available through the GeoModel project website (www.geomodel.pl/en), where also by the end of the project (end of February 2025) a user manual should be published, as well as links to other services from where one can download the entire package and install it as one of the Python libraries.

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