Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Calculation of Geothermal Stored Heat from a Numerical Model for Reserve Estimation

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Keywords: stored heat numerical model

ABSTRACT

The assessment of stored heat in a geothermal reservoir is one of the recommended methods by the AGRCC Geothermal Lexicon for the estimation of a geothermal reserve. Prior to development, when very little information about the reservoir properties is known, the reservoir stored heat is usually estimated using probabilistic methods to find a first guess and an uncertainty range.

Once development of a geothermal reservoir has begun it is quite common to generate a numerical model and calibrate it vs. observed field data. This means that the reservoir properties needed for the calculation of stored heat are more constrained once the model is calibrated. By running a simulation through the calibration time and through a future development scenario one can calculate stored heat at each time step and thus get detailed information about the recovery factor, which is a key uncertainty in the initial stored heat estimation.

A drawback in using stored heat for the estimation of a geothermal reserve is that it only calculates heat in place at a given time. If applied over the complete numerical model domain it can overestimate the reserve by an order of magnitude since it would include hot but impermeable reservoir areas. A method is required to determine additional thresholds to exclude the model domain in which fluid extraction would not succeed.

In this study we present a stored heat calculation on a numerical model and the application of thresholds which we believe should be taken into account. In particular we applied a permeability threshold and used wellbore simulation to exclude all areas of the model domain which could not be used for producing fluid. The results of this study could be used in the discussion for defining a standard procedure for the estimation of geothermal reserves from numerical models.

1. INTRODUCTION

Geothermal reserves estimation is still an evolving concept. Among the latest efforts to define and quantify geothermal reserves is the geothermal reporting code prepared by the Australian Geothermal Reporting Code Committee (AGRCC) in 2008 and updated in 2010. Atkinson (2012) proposed a framework for arriving at a proved geothermal reserves value that is consistent with the Australian reporting code and standards used by the oil and gas industry.

The main challenge for the codes and frameworks developed is its limited uptake and universal application across the industry. At best, the reporting codes set the standards for member organizations: the Australian reporting code is a requirement for all Australian Geothermal Energy Association (AGEA) member organizations. The International Geothermal Association's Resources and Reserves ad hoc committee conducted a workshop in 2013 to start the process of developing a framework for geothermal reserves and resources that may be applicable across the industry (Beardsmore, 2013).

In aid of these efforts, a closer look at the reservoir engineering methods that estimate geothermal energy in a system is necessary. In this study, the volumetric stored heat method is reviewed with a view of using numerical models to improve the assessment process.

The volumetric stored heat method described by Nathenson (1975), White and Williams (1979) and by Muffler (1979) assesses the potential of geothermal systems by estimating recoverable heat from the total thermal energy stored in a volume of porous and permeable reservoir. The recoverable heat is estimated using a recovery factor, R_g. The electrical generating capacity is calculated by estimating the maximum available work, W_A, from the recovered thermal energy and then applying a utilization efficiency, η_u (Muffler, 1979).

The methodology for volumetric stored heat has undergone reviews and updates to improve its applicability. In 2008, Williams et al. reviewed the USGS volumetric stored heat method to update the minimum temperature for electric power production to 90°C and to revise the recovery factor, R_g, among others. A review by Garg (2010) focused on the uncertainties in subsurface parameters, arguing for probabilistic parameter distributions based on actual data. Garg and Combs (2011) did another review, this time on the conversion of available work into electrical energy based on specific power cycles. The AGRCC (2010) reviewed the stored heat method as one of the widely used resource assessment methodologies and presented recommendations on how the method can be applied for resource estimation, e.g. using a simpler conversion 'efficiency' based only on the ratio of electricity produced and the net energy withdrawn from the reservoir. Recently, Zarrouk and Simiyu (2013) proposed adding a natural thermal output term, q, to the stored heat equation for systems with a significantly high thermal output, e.g. Wairakei.

The aforementioned reviews and updates focus on the application of the stored heat resource assessment at the early stages of a geothermal development. The stored heat estimate is rendered obsolete once a reservoir numerical model is built. While resource assessment shifts to numerical modeling results, a refinement or update of the stored heat calculation using the numerical model is not usually done but is not impossible (AGRCC, 2010).

Numerical simulation-based stored heat assessment will be able to address the dynamic changes to the thermal energy as affected by recharge and injection—energy flows into and out of the pre-defined resource volume. The resource volume may also be dynamically changing as the resource volume, defined by a minimum reference temperature, shrinks or expands by injection or hot or cold recharge. In this study, it is proposed that the significant uncertainty in estimating the fraction of recoverable stored heat from a reservoir may be better understood through a look at the recovery factor from a numerical model based on a defined set of subsurface parameter filters or cut-offs.

2. METHODOLOGY

The concept of stored heat in a geothermal reservoir can be adapted for calculating the heat stored in a computational volume element in a numerical model:

$$Q_i = V_i * \{[C_r * \rho_r * (1-\varphi) * (T - T_f)] + [\rho_s * \varphi * \mathrm{SG} * (\mathrm{h_s} - \mathrm{h_w})] + [\rho_\mathrm{w} * \varphi * (1 - \mathrm{SG}) * (\mathrm{h_w} - \mathrm{h_{wf}})]\}$$

where Q_i is the heat stored in element *i* with volume V_i, C_r is the specific heat of the rock, ρ_r the rock density, φ the rock porosity, T the current temperature in the element, T_f the rejection temperature, ρ_s the steam density, SG the gas saturation, h_s the specific enthalpy of steam, h_w the specific enthalpy of liquid water, ρ_w the density of liquid water and h_{wf} the specific enthalpy of water at rejection temperature.

In typical geothermal numerical models the distinction is made between grid blocks (which represent geometric shapes) and volumetric computational elements which usually represent fracture and matrix elements. A grid block can contain multiple elements, for example one fracture element and one or more matrix elements. We will from here on only consider the heat stored in grid blocks, which is simply the sum of the heat stored in the individual elements in the block.

It should be noted that the stored heat needs to be converted into another entity, for example electricity, via an extraction and conversion process. The detail of this process is not a subject of the investigation here.

The reservoir model which we will consider here is a simple in-house-built process model containing ~2900 grid blocks, each containing a fracture and a matrix element. It contains some production and injection wells and is run over a ~13 year period using TOUGH2 in EOS1 (pure water).

Output data is created each year during the run and converted into a *Visualization Toolkit* (VTK) data format. This data format contains all the thermophysical properties (like pressure, temperature, gas saturation) during the simulation plus the static properties (like geometric shape, volume, rock density, porosity, permeability, etc.) in a compact file format that can be visually explored via *Paraview* or used for further data analysis using *Python* scripts. A great advantage of VTK is that a broad range of filters or selection criteria can be easily applied to the data.

2.1. Influence of the Rejection Temperature

Using this VTK format we first calculated the stored heat in each grid block. The only parameter not accessible through simulation output is the rejection temperature T_f. While the *Geothermal Lexicon* includes a discussion about how T_f can be estimated for a geothermal reserve we wanted to investigate its influence on the overall stored heat during a numerical transient simulation. Hence we did not use it as a fixed parameter and used it as a variable for our investigation.

Using a *Python* script on the VTK data we applied a threshold filter on the temperature of the individual grid blocks. The threshold filter selected only blocks with $T > T_f$. On this selection the total stored heat in the reservoir was calculated by summing up the stored heat of the individual blocks. The resulting stored heat is shown in Figure 1; the blocks selected through this process are shown in Figure 4.

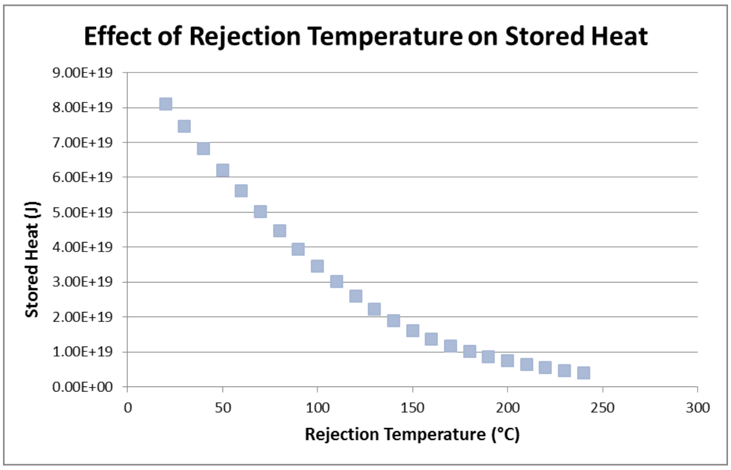

Figure 1: Stored Heat as a function of Rejection Temperature T_f.

The results clearly demonstrate the importance of the rejection temperature parameter. Depending on the application, e.g. domestic heating versus electric power generation, the stored heat available as a reserve varies by an order of magnitude.

Next we investigated the relative change in the stored heat after 13 years of producing the field in the model. The same methodology of using the temperature threshold filter and calculating the stored heat was used during the transient period of the simulation: the stored heat after 13 years of production was compared to the initial stored heat for each of the rejection temperatures under investigation. The results are shown in Figure 2.

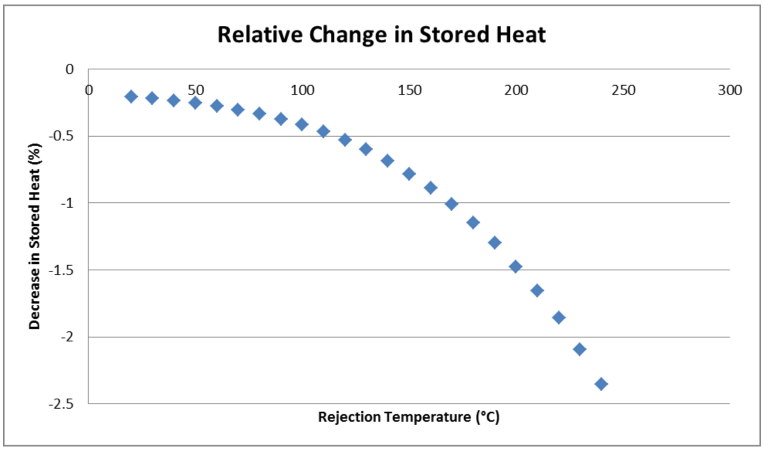

Figure 2: Relative change in stored heat after 13 years of production.

The relative change in stored heat in the model only varies between 1 and 2.5%. At the rejection or base temperature recommended by the *Geothermal Lexicon* of about 150°C (e.g. separator temperature) the change is only about 0.8%. Extrapolated to a project lifetime of about 30 years this implies that the project would only extract 2-3% of total stored heat. This suggests that either a larger plant than the one implemented in the model could be chosen, or – more likely – that a reserve estimation based on the rejection temperature alone is too progressive.

2.2. Permeability Threshold Filter

In order to further constrain the recoverable reserve in the model a permeability threshold filter was applied after the rejection temperature was set to 150°C. The stored heat as a function of the threshold permeability is shown in Figure 3. For very low permeability thresholds (<1mD) the stored heat has only a slight dependence on the permeability threshold, i.e. only a small number of grid blocks get rejected. Above 1mD a noticeable transition occurs, quickly reaching a minimum above around 100mD.

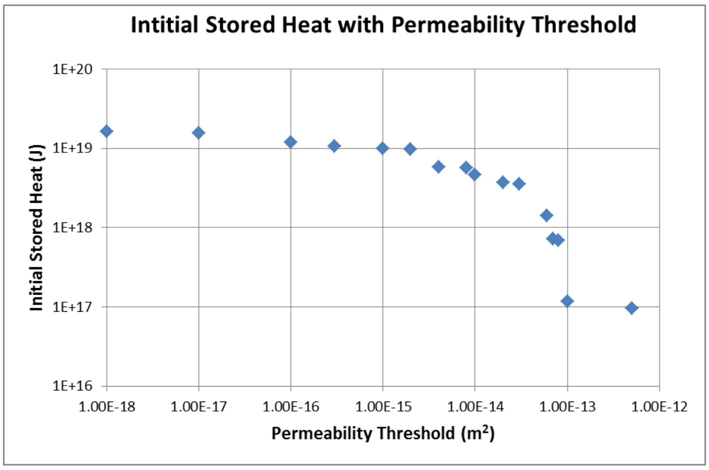

Figure 3: Stored heat at the beginning of the simulation as a function of the permeability threshold.

It is probably difficult to come up with a "best guess" for an appropriate permeability threshold, but Figure 3 displays the key criteria: The stored heat is made up of sections of very-low, low, intermediate and high permeability. Since a key criteria for the definition of a reserve is that fluid can be transported through the porous media and towards a wellbore, it is a reasonable choice to select the threshold at a range which is commonly thought to be acceptable, i.e. around 10mD.

The effect of a 10mD threshold filter can be seen in Figure 4. The left hand picture depicts the selected region using only the 150°C threshold filter. The picture in the center shows the effect of applying the permeability threshold filter. This clearly cuts out significant regions adjacent to the main reservoir that are hot due to thermal conduct with the reservoir but non-conductive.

2.3. Flowing Wellbore Filter

To even further constrain the reserve from the model a flowing wellbore filter was applied. Applying a wellbore simulator individually to each block was considered too difficult at this stage; therefore a lookup table was constructed. A standard wide bore well with a single feedzone at -1000mRL and a PI of $10^{-12}m^2$ was set up in the wellbore simulator GeoWell (supplied to MRP by Mauro Parini, PhD). The pressure was varied between 100 to 200 bar, and the enthalpy was varied between 800 to 2800 kJ/kg. The resulting mass flow rates at the wellhead were calculated with the wellbore simulator creating a 2D-lookup table.

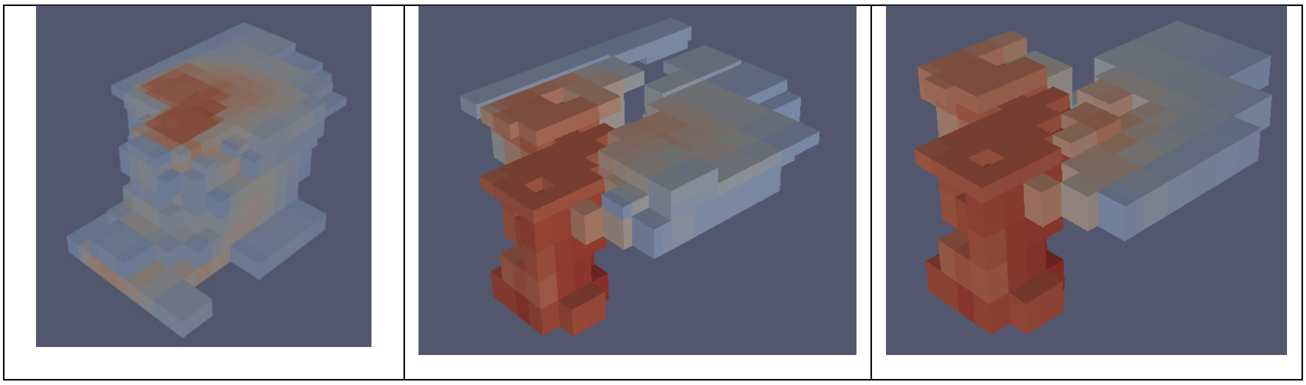

Figure 4: Effect of successive filtering on selected grid blocks. Left to right: rejection temperature, permeability and wellbore simulation filters.

To apply this lookup table to the model data, a pressure and enthalpy correction was necessary. The pressure in each grid block was corrected according to

$$P(Z) = P_0 + \rho_H * g * (Z_0 - Z)$$

where P_0 is the pressure in the grid block, ρ_H the fluid density and Z_0=-1000m. The enthalpy in each grid block was corrected to flowing enthalpy using an adequate relative permeability function.

This method for calculating the flow at wellhead for each grid block is coarse and ideally a wellbore simulator should be run on each grid block individually; however the lookup table method suffices as an approximation and displays the desired effects.

Once the mass flow rate at the wellhead was calculated, another threshold filter was applied using 1 kg/s as a cut-off. The effect is shown in Figure 4; the right hand picture shows the effect of the flowing wellbore filter, which discards further regions from the reserve.

Figure 5 shows a plot where rejection temperature was varied again and includes a comparison with the applied filters. It demonstrates the drastic effects that these filters have versus using the rejection temperature alone for determining the reserve. At 150°C rejection temperature, the reserve estimate after filtering is only about 25% of the reserve estimate from the rejection temperature alone.

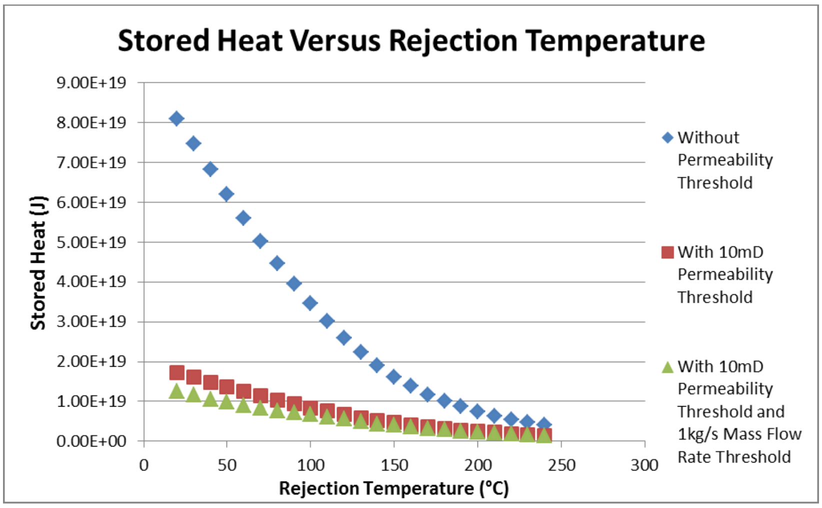

Figure 5: Effect of permeability and flowing wellbore filters on stored heat.

Figure 6 shows the relative change in stored heat using the additional filters. The red data depicts the evolution of stored heat using only the 150°C rejection temperature filter; the blue data shows the evolution using the permeability and flowing wellbore filters in addition. Of course the data with the additional filters starts from a lower base value at time 0; hence the change in stored heat is more pronounced and reaches just over 4% in year 12. Projected to a 30 year project lifetime this yields about 10% decrease in stored heat – i.e. a 10% recovery factor.

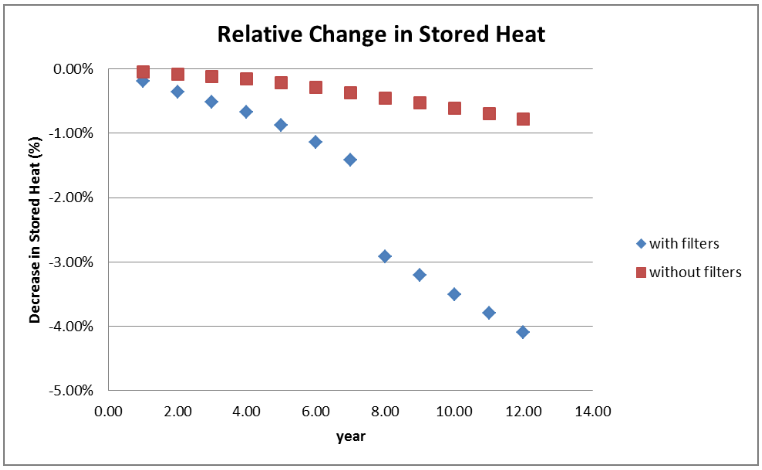

Figure 6: Relative change in stored heat over time. The data in red displays the stored heat using only a rejection temperature filter; the blue data depicts results using additional permeability and flowing wellbore filters.

3. DISCUSSION

The work presented here aims to find a procedure for determining realistic geothermal reserve estimation from a numerical reservoir model. The determination of the amount of stored heat from a numerical model is relatively simple; however constraining the amount of stored heat *accessible* for extraction has proved difficult.

As shown above, the calculation of a reserve based on a rejection temperature alone overestimates the reserve significantly. The additional thresholds filters for permeability and a flowing wellbore are necessary to further constrain the reserve. It would be useful to develop guidelines, i.e. for the *Geothermal Lexicon*, as to how these filters should be applied for reserve estimation.

Also it has been shown that the filters applied in this work are probably still not constrictive enough. The 10% recovery factor estimated for the model is still very low. However, as shown in the filtered picture in Figure 4, there are still regions belonging to the outflow of the modeled reservoir which are considered to be part of the reserve. These should probably be excluded since they would be uneconomic to exploit. For instance, a simple filter could be to exclude all regions above the suspected capping structure. Further economic filters could be developed; these additional filters would decrease the resource estimation further and hence lead to the determination of a more realistic extraction factor for reserve estimations.

Lastly we recommend that the rejection temperature should be defined for the surface technology used. The Geothermal Lexicon in its current state is too ambiguous regarding the rejection temperature and we would recommend that a standard for determining the geothermal reserve of a reservoir should list situation-dependent rejection temperatures.

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