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

Heat Extraction from Deep Single Wells

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Keywords: Direct Heating, Closed Loop, Single Well, Standing Column Well

ABSTRACT

Policies within the European Union are encouraging member states to reduce carbon dioxide emissions associated with the production of electricity and heat. Overall, in Europe, residential heat demand accounts for approximately 35% of the entire annual energy consumption. There is therefore a focus on promoting renewable heat technologies. Such technologies include ground source heat pumps, biomass and deep geothermal heat.

Deep geothermal heat has not, to date, contributed meaningfully to the overall renewable heat supply in Europe. This has been due to the geographical distribution of suitable geothermal aquifers, the high cost of drilling and, more recently, permitting/seismicity issues. To enhance the overall development of the deep geothermal resource, Geothermal Engineering Ltd was funded by the Department of Energy and Climate Change in the United Kingdom to design and test new methods of extracting deep geothermal heat from single wells. This paper reports on the modelling and design of deep geothermal heat exchangers to work in varied geological conditions where the temperatures are suitable for direct heat use in buildings. Of particular interest is the possibility of using wells that have already been drilled for other forms of energy (e.g. shale gas and oil wells). A trial system will be installed in an existing two kilometre deep well in the UK in mid-2014, with commercial installations to follow.

1. INTRODUCTION

Within Europe, there are a number of policy drivers aimed at reducing carbon dioxide emissions associated with electricity and heat production. As residential heat demand accounts for a significant proportion of the overall energy consumption in Europe (IEA, 2011) various initiatives have been developed to encourage the development and supply of renewable heat. In the United Kingdom, a subsidy system has been introduced, the Renewable Heat Incentive (DECC, 2011), to encourage developers to install and make use of renewable heat systems. The overall renewable heat strategy in the United Kingdom aims to make use of a variety of different sources of heat, including deep geothermal (DECC, 2012). According to recent studies, the potential deep geothermal heat resource in the United Kingdom is the equivalent of more than the current annual heat consumption (SKM, 2012). However, the development of the resource to date has been slow, due to the cost of drilling and developing multiple-well systems also known as doublets or triplets, and the uncertainty associated with drilling into unproven resources. In an attempt to speed up the development of the deep geothermal resource, Geothermal Engineering Ltd has been funded by the Department of Energy and Climate Change to design, test and develop so called ‘single deep geothermal well’ systems. The ultimate aim of this project is to have an ‘off the shelf’ system that could be installed in almost any geological environment, irrespective of permeability, therefore significantly reducing the investment risk currently associated with deep geothermal projects. This paper reports on the design of the system and subsequent papers will discuss the fitting and trial of the system.

2. POTENTIAL SYSTEM CONFIGURATIONS

Three possible system configurations were considered to have potential to deliver direct heat from a deep single well. These are shown in Figure 1 and comprise of:

1. A ‘closed loop’ U-Tube system
2. A ‘closed loop’ Co-Axial system
3. An ‘open loop’ standing column system.

2.1 Closed U-Tube

The closed U-Tube is in some ways similar to that deployed in traditional, shallow vertical geothermal systems. However, unlike shallow geothermal systems, the extraction ‘Up’ pipe is insulated to prevent heat loss. Heat transfer occurs by conduction only and therefore the design is independent of the supply and quality of the ground water. The peak energy yields for this design are likely to be the lowest of the three considered here.

2.2 Closed Co-Axial

Like the U-tube design, the Co-Axial configuration transfers heat from the rock to the well by conduction only. However, as the central ‘Up’ pipe is encased by the larger ‘Down’ pipe, there is greater heat transfer through the outer wall, and greater insulation as the heated water travels to the surface. Again, the design is independent of the supply and quality of ground water.

2.3 Open Loop

The Open standing column design is similar to that used in traditional standing column well systems. Water is drawn up from the base of the well, the heat dissipated to the building and the cooler water returned to the top of the well to maintain the water level. As this system transfers heat by both conduction and convection it can provide higher temperatures and higher yields than the closed loop system. The well is also easier to 'bleed' as the pipework is already in place. This system does, however, make use of groundwater and therefore is likely to have higher maintenance levels than the other two designs.

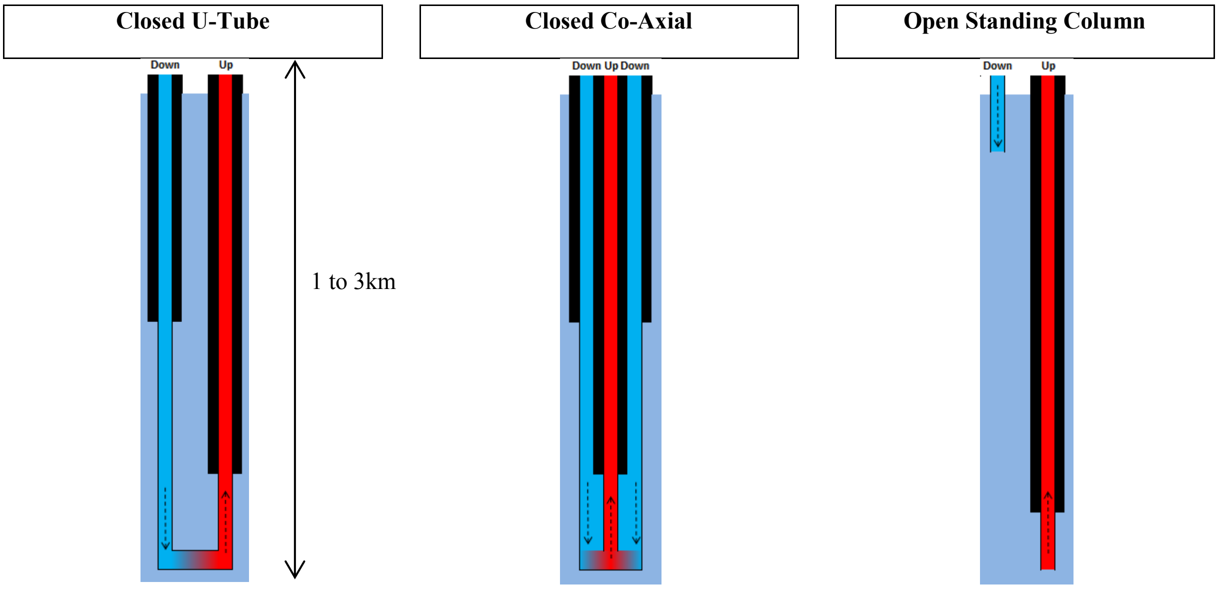

Figure 1 Configurations considered for a deep geothermal single well configuration

The actual system deployed at a potential site will be influenced by the building heating demand profile and the geology at the site. All of the above configurations will need to have the potential for bleed flow to enhance energy transfer rates during times of peak demand. For the three systems listed above, analytical modelling was undertaken to understand potential peak energy transfer rates.

INITITIAL MODELLING

As the majority of the well will be cased with steel, heat transfer through the casing will be almost instantaneous. Therefore, heat transfer through the pipework will be the determining factor for the rate of energy transfer. This transfer is dependent on the thermal resistance and diameter of the pipework and the internal water flow rate. The thermal resistance (R_{layer}) of the pipe is calculated using the following equation:

$$R_{layer} = \frac{\ln(r_e / r_i)}{2\pi\lambda_k} \quad [\mathrm{m.K/W}]$$

Equation 1

Where:

r_e = the outer radius of the pipe [m]

r_i = the inner radius of the pipe [m]

λ_k = the thermal conductivity of the pipe material [W/m.K]

The total thermal resistance of a pipe (R_{tot}) and surface heat transfer resistances (R_i and R_e) to inner fluid and external well water can be calculated with following equation:

$$R_{ltot} = \frac{R_i}{2\pi r_1} + \frac{\mathrm{R_i}}{2\pi \mathrm{r}_1} + \sum_{\mathrm{k=1}}^{\mathrm{n-1}} \frac{\ln\left(\frac{r_{(k+1)}}{r_k}\right)}{2\pi\lambda_k} + \frac{\mathrm{R_e}}{2\pi \mathrm{r_n}} \quad [\mathrm{m.K/W}]$$

Equation 2

Where:

R_i = inner surface heat transfer resistance between fluid and material [m^2.K/W]

R_e = outer surface heat transfer resistance between fluid and material [m^2.K/W]

To optimize the initial design of the system, the following parameters were assessed for their impact upon the thermal performance:

- Cross-sectional dimensions of the pipe
- Thickness of insulation layer
- Depth of well
- Well temperature at surface
- Water injection temperature
- Temperature gradient with depth
- Percentage of Up and Down pipe insulation
- Flow rate
- Thermal conductivity of pipe
- Thermal conductivity of insulation layer

An important initial assumption of this initial analytical modelling is that well temperatures are constant and stratified, so heat transfer from the rock is sufficient to replace the heat extracted. In practice, this will not be the case as energy abstraction rates increase. This impact is addressed in the numerical modelling (i.e. dynamic modeling) discussed later in this paper.

The well modeled is 2.5 km deep, with a temperature gradient of 30°C/km and is similar to the proposed well to be used in the field trial. The temperature at the base of the well is therefore 85°C. The re-injection temperature at the surface has been set at 50°C to reflect a potential return temperature from a district heating network. The actual injection temperature will vary, depending on the eventual use of the heat at a development site. The chosen flow rate (3 litres/ second) reflects the trade-off between parasitic pumping loads and peak energy delivered. Further, given that some degree of bleed flow is expected to be required during peak periods of energy abstraction to replenish heat, it was assumed that a periodic bleed flow rate of 3 litres/ second would be achievable from the majority of suitable wells. The results of the initial modelling show that, without bleed flow, the designs can supply between 173 kW and 393 kW of heat to the surface with the heat being delivered at a minimum temperature of 63.8°C.

Table 1 Summary of initial design results

	Closed U-Tube	**Closed Co-axial**	**Open Standing Column**
Delivery Temperature	63.8°C	68.7°C	81.3°C
Injection Temperature	50.0°C	50.0°C	50.0°C
Total Energy supply at 3 l/s	173 kW	235 kW	393 kW

Although open systems typically yield more thermal energy than either of the closed loop configurations (as shown in Table 1), open systems have two general disadvantages:

1. Maintenance costs will be higher due to using deep well water of poor quality in heat exchangers
2. The parasitic pumping power will be higher due to the need to lift water from the well, as opposed to just circulating the water within a closed system

Thus further analysis was undertaken only on the U-Tube design and the Co-Axial design to understand whether designs could be significantly improved and practically installed in the well. The main parameters to be considered are inter-dependent and these relationships are summarised in Figure 2.

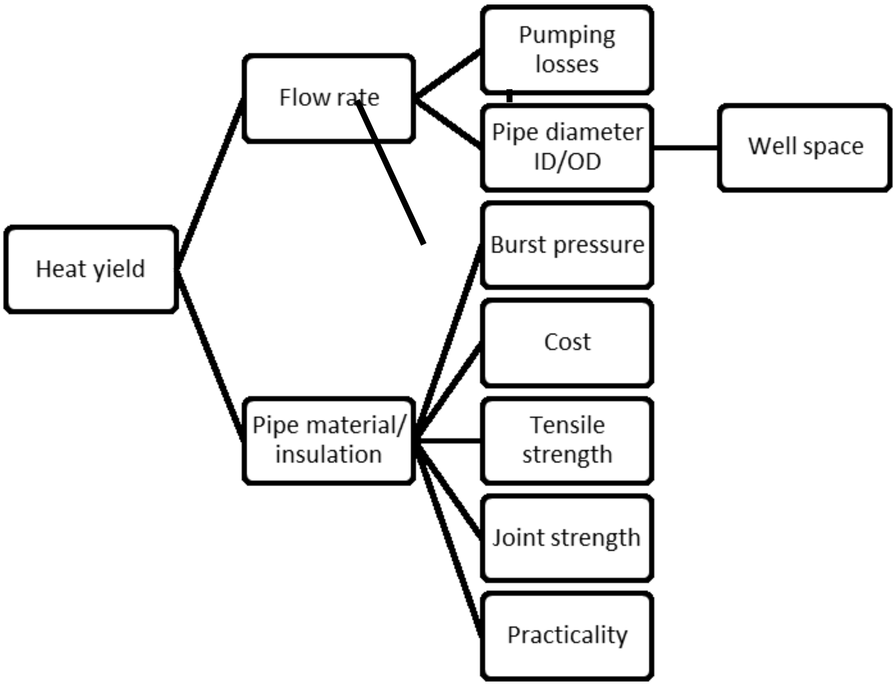

Figure 2 Interdependent relationships for the single well system

Figure 2 shows that the system will be strongly dependent upon the choice of pipe material and/ or insulation and, to a lesser extent, the flow rate. The first step in the design process was therefore to evaluate a number of different materials for suitable properties including tensile strength, burst pressure, weight in water, thermal conductivity and cost.

For the given pressure and temperature conditions in a 2.5 km well, the following criteria were set for the materials to be used in the well. The difference between the static pressure within the pipework and external to the pipework will be effectively zero at any depth. Therefore, the only pressure that the pipework needs to withstand is that generated when pumping fluid around the pipework. This pressure is dependent upon the flow rate and the diameter of the pipework. The criteria required for the well are listed in **Table 3**.

Table 2 Criteria for the materials chosen for the single well

Tensile strength	**Burst pressure**	**Weight (in water)**	**Thermal conductivity**	**Cost (£/ km)**
Must be able to easily support 2km of pipework in water (dependent on the weight of the pipe in water and the tensile strength of the material)	The net static pressure on the pipe will be zero at any depth. However, the pipe must be capable of withstanding the pressure generated from a maximum flow rate of 5 l/s within the pipe at all depths. This equates to a maximum of 6 MPa in the down-pipe and 2 MPa in the up-pipe (this applies to the majority of possible pipework diameters)	The heavier the material is in water, the greater the required tensile strength of the material	Greater than 20 W/mK for the down-pipe. Less than 0.4 W/mK for the up-pipe	Less than £45,000 per km

Table 3 Criteria for the materials chosen for the single well

For any materials that could potentially be used in the well the U-Tube and Co-Axial designs were evaluated for the following criteria:

1. Maximum heat yield (flow and temperature)
2. Achievable flow rate
3. Pipe diameter (ID/OD)
4. Parasitic pumping power
5. Space in the well

6. Practicality of construction

7. Cost

The evaluation showed that although the co-Axial system has a slightly lower parasitic pumping loss than the U-Tube design and can potentially deliver a marginally higher heat load it has the following disadvantages:

1. Higher cost of material. The larger diameter steel pipework required for the outer layer of the co-axial pipe increases the cost of the system significantly (approximately threefold) over the U-Tube design

2. The pipework takes up a significant volume of the well, leaving very little space for a bleed pipe

For the U-Tube design therefore, further analysis was undertaken to optimise the system performance in terms of yield, parasitic pumping power and internal pressure for different diameters of pipework and flow rate. Particular attention was given to pipework diameters (ID and OD) that were both fit for purpose and could be purchased 'off the shelf'.

3.0 NUMERICAL MODELLING

For the planned field test and, perhaps more importantly, future commercial installations of the deep geothermal single well system, a dynamic model of the well/ heat demand profile needs to be constructed and validated. This model can be used to test how the system will perform under different geological conditions and energy demands. Given that the energy demands of a building will vary significantly throughout the year and the temperature of the well will react to both energy abstraction and bleed flow, the numerical model must be able to simulate transient energy and ground water flow. Although there are a number of numerical codes available for this type of analysis, SUTRA 3D (released by the USGS) was selected due to extensive prior experience within the development team.

3.1 Model construction

To optimize model convergence time and reduce the size of a model, symmetry was used to divide the well into quarters and the principal model features are shown in Figure 3.

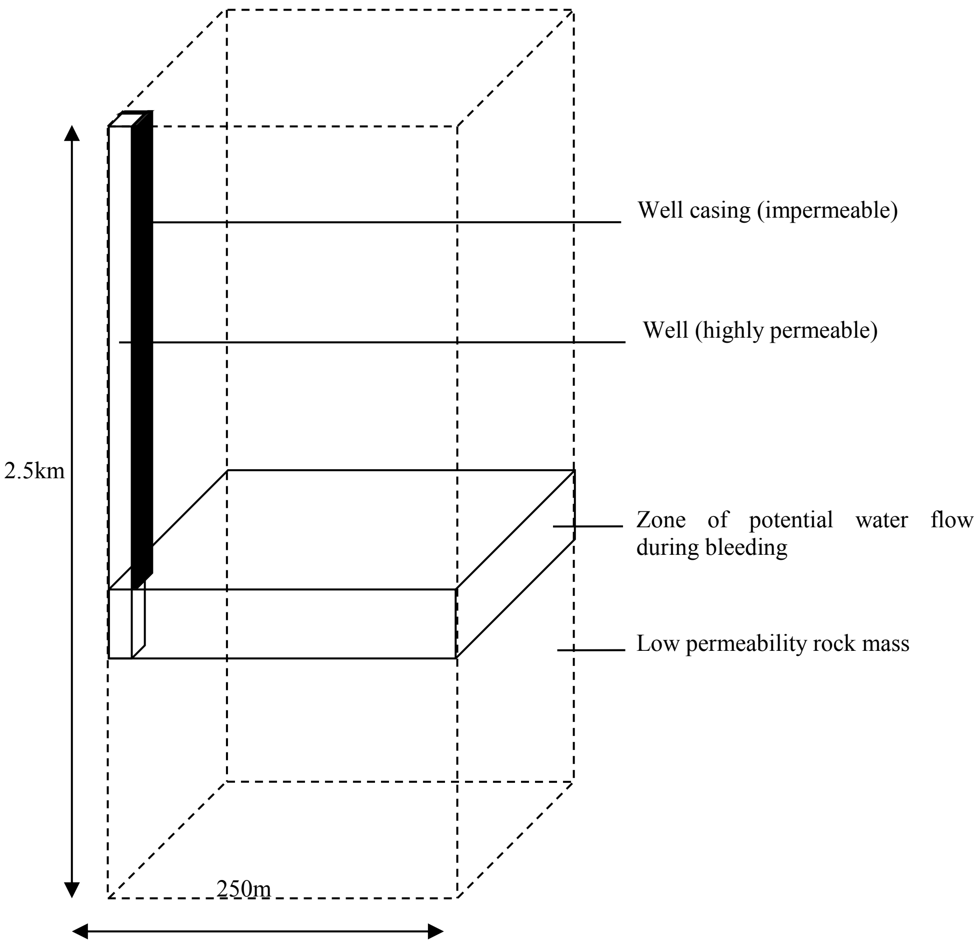

Figure 3 Principal model features and dimensions

3.2 Discretisation

Determining the appropriate grid size for numerical models is a tradeoff between computer power (which dictates the convergence time) and the definition required to provide adequate solution accuracy. The greater the definition, the larger the model and thus the more time it takes to run the model. In regions of the model where the temperature gradient is high, the grid size and time steps must be small enough to provide an adequate solution. The transition points presented between these tradeoffs can be quantified numerically using the Mesh Peclet number and the Courant Number.

The spatial stability of the numerical approximation of the transport equation in SUTRA 3D depends on the value of the mesh Peclet number, Pe_m given approximately by:

$$Pe_m \approx \frac{\Delta L}{\alpha_L}$$

Where:

ΔL is the local distance between element sides along a streamline of flow

α_L is the dispersion coefficient

Spatial instability appears as one or more oscillations in concentration or temperature. Stability is guaranteed in all cases when the Pe_m value is less than 2, which gives a criterion for choosing a maximum allowable element dimension, ΔL, along the local flow direction. This criterion significantly affects discretisation. Spatial stability is usually obtained with SUTRA 3D when the Pe_m value is less than 4, which gives a less-stringent criterion. Mesh design according to the criterion is critical when temperatures change significantly along streamlines, such as when a front is propagated in the direction of flow. When concentrations or temperatures exhibit small changes along streamlines, then the criterion may safely be violated, even by a few orders of magnitude, without inducing spatial instability.

The Courant number relates the time stepping and velocity to the size of each element direction ΔL. It becomes important when the velocity of the fluid is of a similar order of magnitude to the element size divided by the time step. The Courant number is represented numerically as follows:

$$C_o = \frac{\delta t|U|}{\delta x}$$

Where

C_o = the courant number

$|U|$ = the velocity of the fluid

δt = the timestep

δx = element dimension or ΔL

To avoid spurious numerical results it is important to keep the Courant number below 1.

In general, thermal transport within the model will be relatively slow, due to the rate of energy transfer being governed by conduction. However, there will be periods when the well is bled, during which thermal transport will be more rapid and governed by convection. For this reason, the model has a higher level of discretisation in zones near to the well and where convective energy transport is expected to occur.

3.3 Initial conditions

It was assumed that the rock is under linear hydrostatic pressure and the temperature gradient is 32°C per km (as at the chosen trial site).

3.4 Energy abstraction

One of the principal markets for the deep geothermal single well will be heat provision for multiple residential units, typically 100 apartments per well. A number of different models were constructed and run to understand how the well could best be operated to match such a heating profile and to provide a range of data that could be validated during the trial. The model scenarios completed are listed below:

1. Constant energy abstraction at variable rates with no bleed flow
2. Well recharge rate without bleed flow

3. Constant abstraction with low level bleed flow
4. An annual dynamic model using the heating demands from a typical target development without bleed flow
5. An annual dynamic model using the heating demands from a typical target development with bleed flow

3.5 Scenario 1: Constant energy abstraction

During periods of constant energy abstraction, the temperature of the well is expected to decrease. The rate temperature decrease will be governed by the thermal conductivity of the rock, the rate of energy abstraction and the groundwater flow at the site. The thermal conductivity of the rock is a known parameter; the groundwater flow is unknown and at 2.5 km is likely to be negligible.

Economic assessments has suggested that, in the United Kingdom, a deep geothermal single well needs to achieve an annual yield of approximately 1 GWh to be economically viable. This annual supply is likely to consist of varying peak heating demands at different times of the day with a maximum energy abstraction (see previous analytical modeling of approximately 400 kW). The following energy abstraction rates were therefore tested in the model to evaluate how rapidly the temperature of the well decreased. The results are shown in Table 4 and graphically in Figure 4.

Table 4 Thermal drawdown time at the base of the U-Tube for different constant rates of energy abstraction (no bleed flow)

Energy abstraction rate (kW)	50	100	200	400
Time to reduce well temp by 1°C (hrs)	0.34	0.20	0.13	0.10
Time to reduce well temp by 2°C (hrs)	7.4	3.2	1.2	0.5
Time to reduce well temp by 4°C (hrs)	405	80	18	4.3

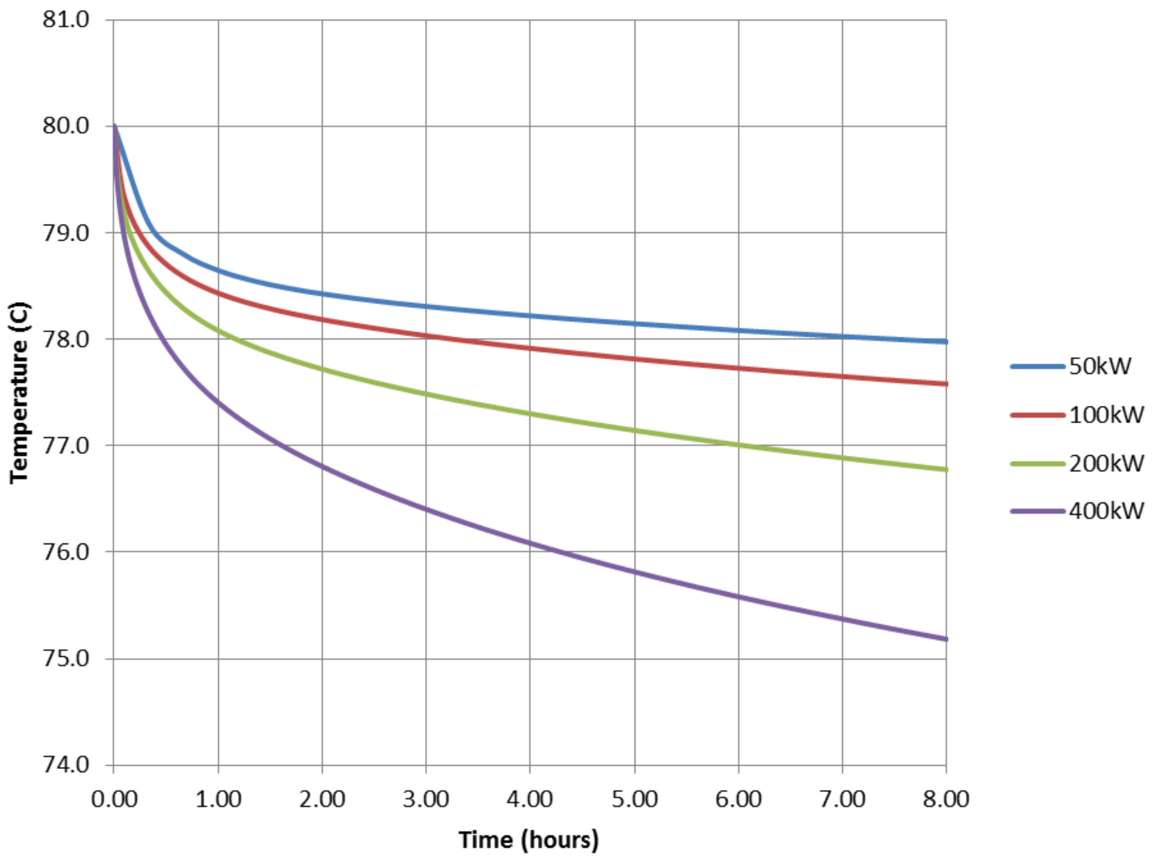

Figure 4 Thermal drawdown at base of the U-Tube for different energy abstraction rates (no bleed flow)

The results of the modeling show that the thermal drawdown rate and well temperature decrease over time as the well and the surrounding rock trend toward steady state conditions. This long-term trend is shown more clearly in Figure 5, where constant energy abstraction has been extended to a period of 10 years. The level of energy abstraction from the well affects both the steady state temperature in the well and the time for the well to reach steady state. At lower constant energy abstraction rates, the well reaches equilibrium after approximately 10 years. The results also suggest that constant energy abstraction at rates higher than 75 kW, without bleed flow, will cause a gradual decrease in well temperature to a level which is not suitable for direct heating. The well would therefore either have to be bled or linked to a ground source heat pump to provide a constant rate of energy supply above approximately 150 kW.

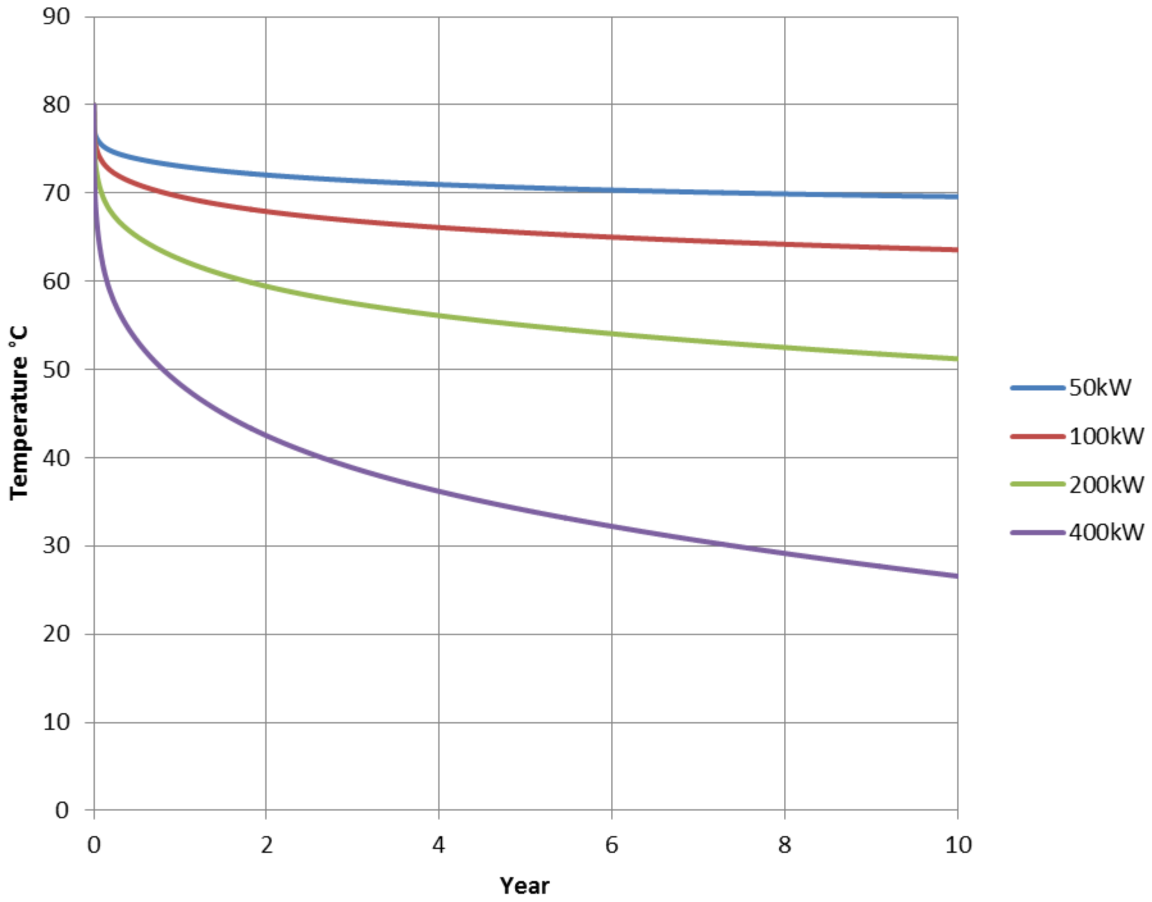

Figure 5 Long-term temperature trend in the well for different constant energy abstraction rates (no bleed flow)

3.6 Thermal recharge rates

As building heating demands are not constant throughout the year, there will be times when the well is not used and thermal recharge can occur through conduction. The model was run for different energy abstraction rates to induce temperature reduction in the well. Recharge rates were then modeled and the results are shown in Figure 6. Without groundwater flow, or bleed flow in the well, the recharge rate decreases over time as the well approaches the initial temperature of 80°C. The greater the thermal drawdown, the faster the initial thermal recharge. Overall, natural recharge rates are relatively slow, generally less than 1°C per hour.

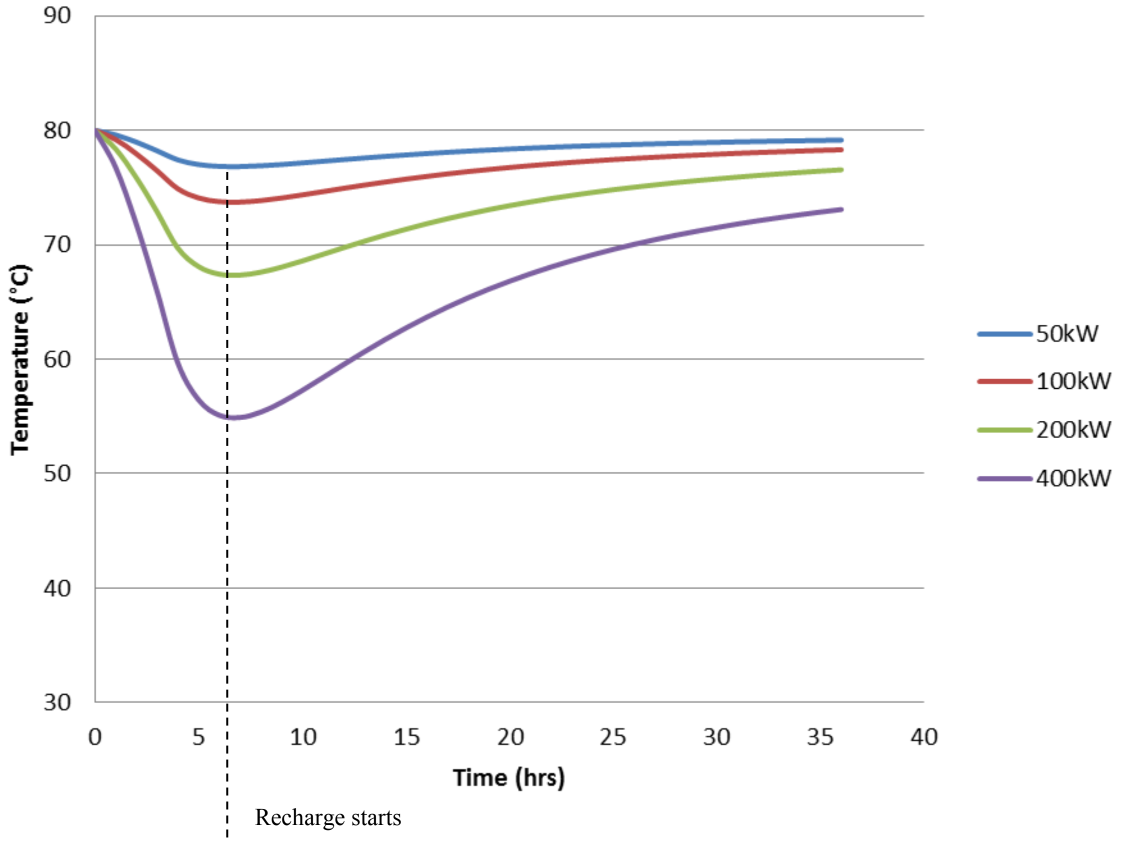

Figure 6 Natural thermal recharge in the well following loss of temperature in the well (no bleed flow)

3.7 Bleed flow

The main effect of bleed flow should be to recharge the temperature in the well at a faster rate than would occur naturally. Given that the well will be cased down to the target depth, the influx of water to the well will be at the highest possible temperature for the well. For the constant energy abstraction rates thus far used in the model, a low level of bleed (2 litres per second) was applied to the well. This level of bleed was chosen because it was assumed that it could be achieved from almost any geological formation. The results are shown in Figure 7.

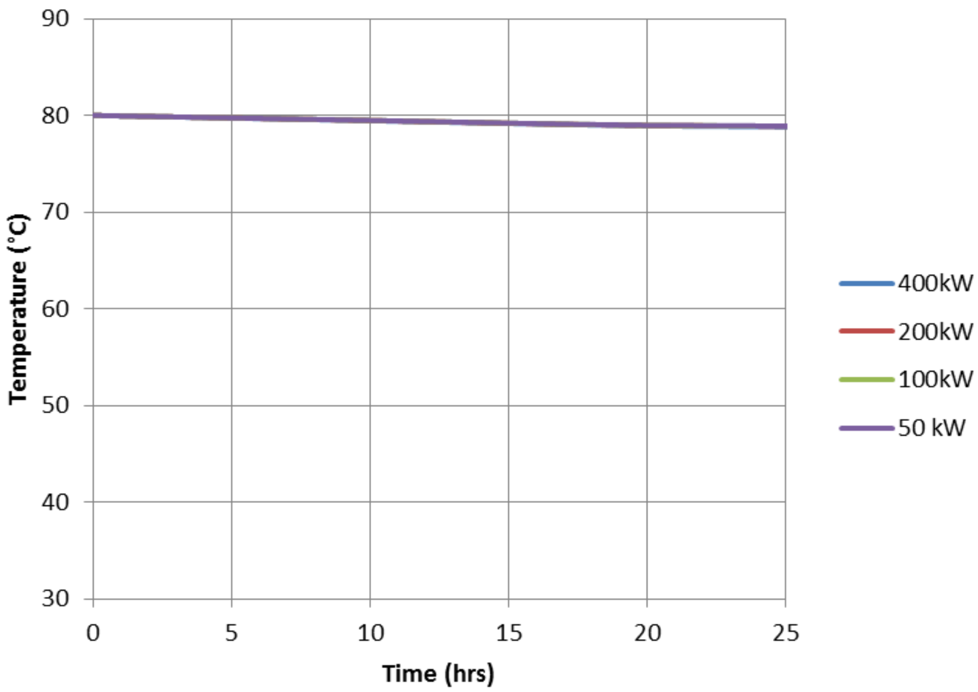

Figure 7 Temperature for different energy abstraction rates with a 2 l/s bleed flow

The results show that for all energy abstraction rates (all of the lines are at approximately the same temperature) even a low level of bleed flow counteracts the degradation of temperature in the well at all abstraction rates. The temperature in the well remains very close to the original 80°C but is slightly lower due to the bleed flow water being drawn from areas of the surrounding rock that are both above and below 80°C.

3.8 Typical building demand

A typical energy profile (heating and domestic hot water (DHW)) for a target residential building with 100 apartments has been provided by Ove Arup and Partners, Ltd (Arup, 2013) and an hourly breakdown of this data is shown in Figure 8. In total this represents an annual heating demand of 1.1 GWh with maximum heat demand occurring in the winter months. It can be seen that the peak loads of 450 kW occur for very brief periods of time in January and December. The annual load equates to a constant energy abstraction of 125 kW.

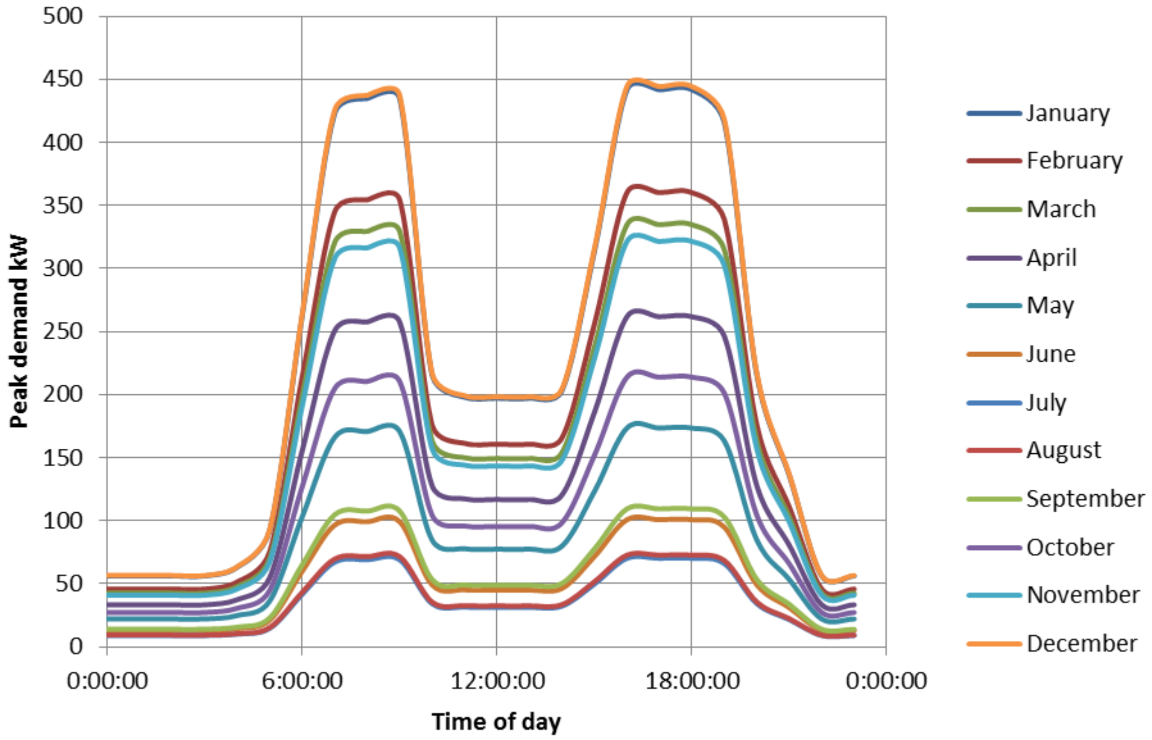

Figure 8 Heating demand profile for a typical apartment block of 100 apartments

For these given heating demands, a transient model was run to simulate the well response with and without bleed flow. The results are shown graphically in Figure 9 and Figure 10. Without any bleed flow, the well temperature drops over the year to approximately 70°C. During the summer months, the well does recharge but not at a sufficient rate to prevent an overall annual temperature decrease. Back calculating the annual loads for the apartments yields a constant energy abstraction of approximately 125 kW. The results shown on Figure 5 illustrates that for a constant energy abstraction rate of 125 kW, the temperature at the base of the well is expected to drop to approximately 70°C after 1 year.

When a low level of bleed is introduced to the well, it can be seen that the temperature in the well is restored to a constant level, close to the original 80°C (Figure 10).

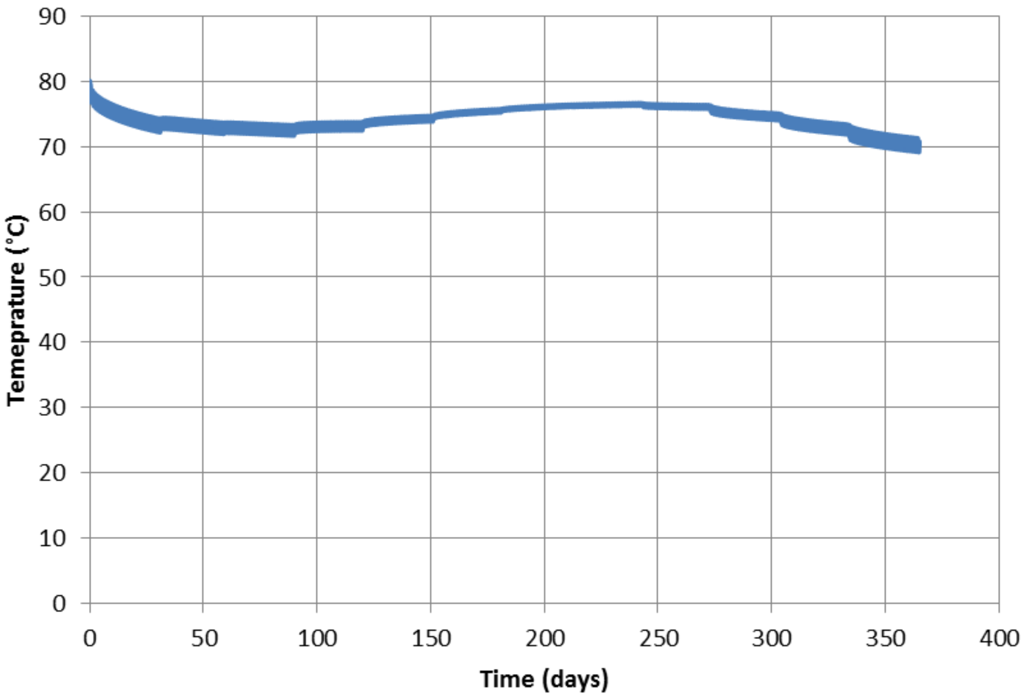

Figure 9 Well temperature profile for the energy demands of 100 apartments (heating and hot water) – without bleed

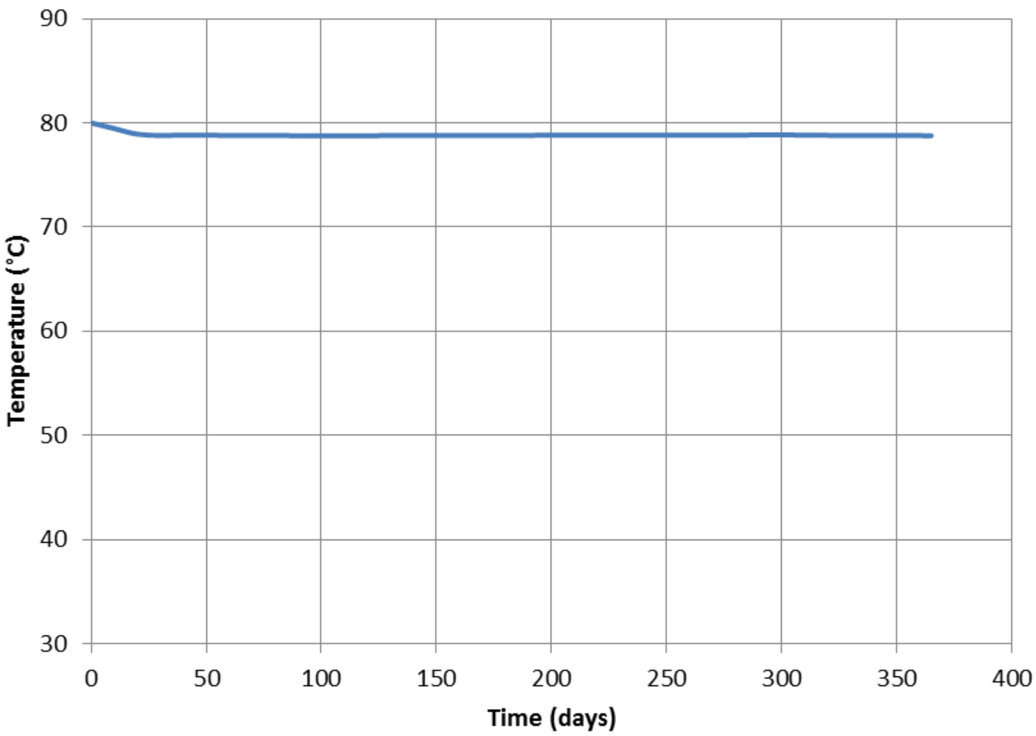

Figure 10 Well temperature profile for the energy demands of 100 apartments (heating and hot water) – with constant 2 l/s bleed

4.0 CONCLUSIONS

The results of the analytical and numerical modelling lead to a number of conclusions about single well systems:

1. Deep geothermal single well systems have the potential to deliver peak loads of around 400 kW in geological environments where low levels of water abstraction are possible
2. If closed systems are to be used, a U-Tube system will cost less than a co-Axial system and provide a similar peak thermal delivery
3. At low energy abstraction rates (<100 kW) energy can be constantly removed from the well without significant thermal drawdown
4. At higher energy abstraction rates (>100 kW), bleed flow will need to be used to limit thermal drawdown in the well or the system will have to be linked to a device that boosts the output temperature.
5. For a variable energy demand (100 apartments) the well temperature will drop over time, approximately at the same rate as the averaged annual energy abstraction rate.
6. Introducing low levels of bleed flow counteracts the temperature drawdown in the well rapidly and effectively

Without bleed flow, the temperature of the well cannot be sustained over time unless only moderate levels of energy are taken out of the well. Low levels of bleed flow can easily sustain the temperature of the well at energy abstraction rates up to 400 kW. Further, depending on the characteristics of the well, higher peak loads could be achieved by periodically increasing the bleed flow. Given the rapid effect of bleed flow, the optimum use of the well will be to trigger bleed flow when the well reaches a specified minimum temperature.

The numerical model should prove to be an invaluable tool when matching a well to a particular building design and the results will be compared to an actual field trial later in 2014. Of particular interest will be whether deep groundwater flow has any effect on the expected thermal performance of the well. A field trial of a deep geothermal single well will be conducted in mid 2014 and the results presented in a following paper.

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