

Influence of Cement Thermal Properties on Wellbore Heat Exchange

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Keywords: cement, heat exchange, thermal conductivity, wellbore construction, efficiency

ABSTRACT

Cementing geothermal wells is not an easy task. Besides the high temperature environment that affects the curing time of the cement, the cement sheath behind the casing, which is used primarily to protect and hydraulically seal the wellbore, influences the heat exchange from the wellbore to the formation and vice-versa.

Depending on the geothermal operation, high or low heat exchanges might be preferred. For example, operators aim for a high and constant heat exchange in the lower part of a geothermal well and try to insulate the upper part of the same well in order to minimize heat and efficiency losses accordingly.

This study focuses on the ability of different cements' thermal conductivities to influence the heat exchange in various wellbore segments under assumed static conditions.

The results of sensitivity analyses indicated which parameters play crucial roles while modeling the heat transfer in high temperature boreholes. Via Monte Carlo simulation, the relative importance of diverse thermal and geometrical parameters was considered when calculating the rock formation/wellbore heat exchange. The modeling highlighted the presence of a 'working window' in which the variation of the thermal or geometrical parameters can strongly influence the borehole-formation heat exchange.

Finally, the paper provides the optimum cement thermal properties required to properly cement a geothermal well and so minimize/enhance heat exchange to/from the wellbore.

1. INTRODUCTION

Geothermal wells resemble oil and gas wells and are constructed in a similar way before being used in the production phase (Falcone and Teodoriu, 2008). Geothermal 'hard' formations such as granite, basalt and volcanic tuff, coupled with the need of larger tubulars in geothermal projects (Warner, 2007), present a particular set of challenges, not only during cementing operations, but also throughout the life of the well (integrity related issues).

The cement sheaths behind every casing component, which are used for protecting and sealing the wellbore, are a central element of every well. The current industry standard is Portland cement, which is a mixture of burned limestone, clay, and different additives that fulfill various purposes. The need of understanding and designing such cements for high pressure, high temperature (HP/HT) wells is recognized by the industry (Zeringue, 2005; DeBrujin *et al.*, 2008), since the behavior of cements under increased temperature and pressure diverges from that seen at surface conditions. However, the relatively small number of publications on the topic means there are some questions on the effects of cement thermal properties on well construction that remain unanswered.

Since physically investigating cements under downhole conditions is cost prohibitive and time consuming, it is deemed worthwhile to first appreciate how different thermal properties of cements can influence the transfer of heat in HP/HT wells. For this purpose, sensitivity studies were performed to investigate the different parameters of a representative mathematical model.

2. MATHEMATICAL MODELING

Thermal flow in wells has been mathematically modeled by the industry for over 60 years. When heat flow is simulated, the thermal parameters such as conductivity and heat capacity are considered to be known. For simplicity, often parameters, such as the cement's effect on overall well heat transport, are neglected.

2.1 Thermal Conductivity

An important property of cement is its thermal conductivity (k). This relates to the ability of a material to conduct heat and is defined as the quantity of heat (Q) transmitted through a unit thickness (L) in one direction normal to a surface of unit area (A) due to a unit temperature gradient (ΔT) under steady state conditions, and when the heat transfer is dependent only on the temperature gradient. This definition is described by **equation 1**, after solving Fourier's heat equation for k and assuming a constant temperature gradient:

$$k = \frac{Q \cdot L}{A \cdot \Delta T}, \text{ expressed in } \frac{W}{m \cdot K} \text{ or } \frac{BTU}{hr \cdot ft \cdot ^\circ F} \quad (1)$$

Although important, cement thermal conductivity is often neglected by well engineers, who tend to use a single thermal conductivity coefficient for the entire wellbore. This can lead to flawed well design, especially when temperature is dominant and may alter the properties of the fluids in the well. Conventional cement thermal conductivity can range widely, from 0.2 to 3.63 W/K-m (Neville, 2011; Baghban *et al.*, 2012).

2.2 Physics

Such a wide array of cement thermal conductivities suggests that using a singular thermal conductivity coefficient for the entire wellbore will lead to inaccurate values of the overall heat exchange coefficients. In a model presented by Hasan and Kabir (2002), radial heat transfer occurs between the wellbore and the earth, with the heat exchange taking place in one direction over the tubing wall, insulation, annulus between the tubing and the casing, casing wall and cement, depending on the temperature difference between the formation and the wellbore. The different elements of the path via which the conductive heat transfer must take place resembles an electrical circuit of resistors connected in series. This excludes the annulus, where convection is usually expected. The symmetry along the wellbore and the small vertical temperature gradients transform this three-dimensional problem into a one-dimensional task. At steady state conditions, the rate of heat flow through the wellbore per unit of length (also defined as the overall heat transfer or heat exchange) is:

$$Q = -2\pi \cdot r_{to} \cdot U_{to}(T_f - T_{wb}) \quad (2)$$

where U_{to} represents the overall heat transfer coefficient (in $BTU/(hr \cdot ft^2 \cdot ^\circ F)$), $(T_f - T_{wb})$ is the temperature difference between the wellbore/formation interface and the wellbore fluid and, $2\pi \cdot r_{to}$ is the tubing outside area (ft^2). By convention, a negative heat exchange implies heat flow from the formation to the wellbore and a positive heat exchange denotes the opposite.

The overall heat transfer coefficient in **equation 2** is mathematically described as the inverse of the thermal resistance:

$$\frac{1}{U_{to}} = \frac{r_{to}}{r_{ti}h_L} + \frac{r_{to} \ln\left(\frac{r_{to}}{r_{ti}}\right)}{k_t} + \frac{r_{to} \ln\left(\frac{r_{ins}}{r_{to}}\right)}{k_{ins}} + \frac{r_{to}}{r_{ins}(h_c+h_r)} + \frac{r_{to} \ln\left(\frac{r_{co}}{r_{ci}}\right)}{k_c} + \frac{r_{to} \ln\left(\frac{r_{wb}}{r_{co}}\right)}{k_{cem}} \quad (3)$$

with the following geometrical parameters (expressed in ft.):

r_{to} – tubing outside radius	r_{ci} – casing inside radius
r_{ti} – tubing inside radius	r_{co} – casing outside radius
r_{ins} – insulation radius	r_{wb} – wellbore radius

and the following thermal properties (convective coefficients are expressed in $BTU/(hr \cdot ft^2 \cdot ^\circ F)$ and conductivities in $BTU/(hr \cdot ft \cdot ^\circ F)$):

h_L – liquid convective heat transfer coefficient,	k_t – conductivity of tubing material
h_c – convective heat transfer coefficient	k_c – conductivity of casing material
h_r – radiative heat transfer coefficient	k_{cem} – conductivity of settled cement

The first term in **equation 3** represents the conduction heat transfer coefficient in the tubing/drilling pipe and it can also be written as (Petroleum Experts, 2015):

$$h_{co} = \frac{2k}{d_i \ln\left(\frac{d_o}{d_i}\right)} \quad (4)$$

2.3 Wellbore cases

Several wellbores were set up, with different cement sheath properties, and subsequently used to investigate the relative influences of the various materials on the overall heat exchange. The radiative and convective heat transfer coefficients were neglected as they have been shown to have very little influence on heat transport phenomena in wellbores (Urazgaliyeva, 2015). The lower part of the simulated wellbore was assumed to consist of a 7 5/8" production casing cemented in a 9 1/2" hole, whereas the upper part of the wellbore included a 6 5/8" production string and three concentric casing strings (7 5/8", 9 5/8" and 13 3/8") cemented in a 16" wellbore. Note that this study focused on the wellbore heat exchange and did not consider the open zone part of a typical fractured geothermal well. The thermal conductivities of the simulated wellbore materials at surface conditions were assumed to be: steel – 45 W/m-K, formation rock – 2.5 W/m-K, wellbore fluid – 0.69 W/m-K, air – 0.025 W/m-K; the cement thermal conductivity was varied throughout the calculations. The temperature difference between the formation and the wellbore was set at 104 °F (40 °C) in the lower wellbore section and at 228.6 °F (109 °C) in the upper section. Three different cement recipes were used in the simulations, where pbw indicates the parts by weight:

A: 100 pbw API cement H + 35 pbw silica flour + 59.4 pbw water; equivalent to 35% cement, 33.3% silica flour, 31.7% water by volume.
 B: 100 pbw API cement H + 38 pbw water; equivalent to 63.4% cement, 36.6% water by volume.
 GAluminum: 100 pbw API cement G + 40 pbw water + 10 pbw aluminum powder; equivalent to 60% cement, 3.4% aluminum, 36.6% water by volume.

2.4 Factors influencing the overall heat exchange

The overall heat transfer, formulated in **equation 3**, was modeled with the Monte Carlo technique for the different wellbore cases described above. Monte Carlo simulation is a problem solving technique widely used to estimate the likelihood of a certain expression by running multiple trials, using input variables with defined ranges and distributions. An associated sensitivity analysis, expressed as a Tornado plot, was performed simultaneously to see which variables influence the calculation of the formation-wellbore heat exchange more strongly.

Figure 1 shows that the production tubular outside radius, the overall heat exchange coefficient and the temperature difference between the formation and the fluid all have approximately the same influence on the calculated wellbore heat exchange, according to **equation 2**.

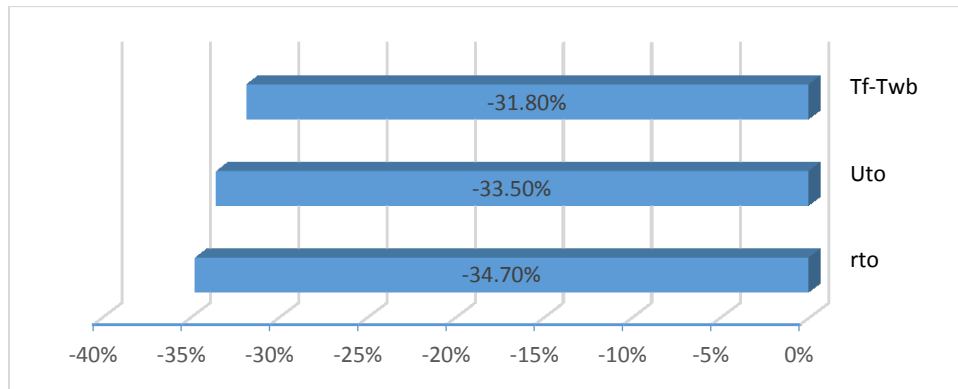


Figure 1 - Heat exchange sensitivity study

As the temperature differential and production casing outside diameter are fixed by formation properties and production necessities, respectively, it was considered worthwhile to further investigate how the one remaining adjustable parameter, the overall heat exchange coefficient, influences the heat exchange in the model.

In order to simulate what influences the heat transfer during the drilling process, one must assume that the first annulus in the upper wellbore section, as introduced in section 2.3, is filled with a drilling fluid. In contrast, in a production scenario, this annulus is usually filled with air, which has a lower thermal conductivity. **Figure 2** shows that by far the most influential parameter in the determination of thermal resistance (and therefore of the overall heat transfer coefficient) (**equation 3**) is the thermal conductivity of the cement, followed by the thermal conductivity of the fluid inside the annulus, while the steel thermal conductivity does not influence this coefficient. When running the same scenario for an upper annulus filled with air, the cement thermal conductivity influences the thermal resistance even further, by over 98%.

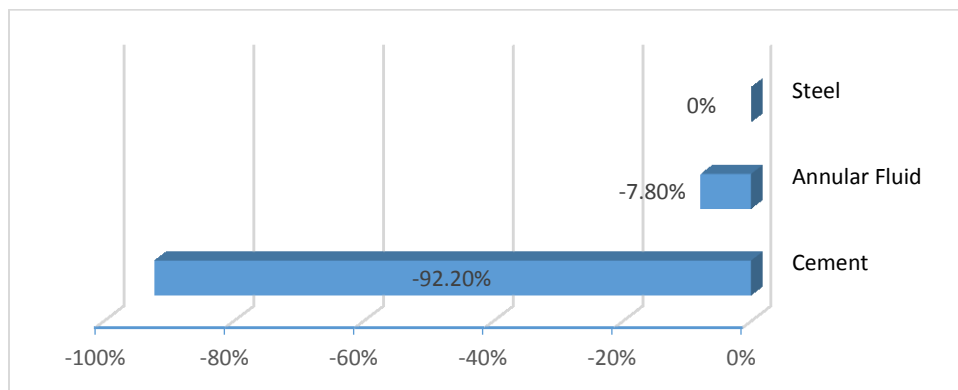


Figure 2 – Thermal resistance - sensitivity study

To better quantify the influence of the cement thermal conductivity on the overall heat transfer coefficient and the heat exchange in the wellbore, U_{to}^{-1} , U_{to} and Q were calculated, initially for the lower wellbore section, using values of the cement thermal conductivities from 0.1 BTU/hr-ft-°F (0.173 W/m-K) to 6.5 BTU/hr-ft-°F (11.245 W/m-K).

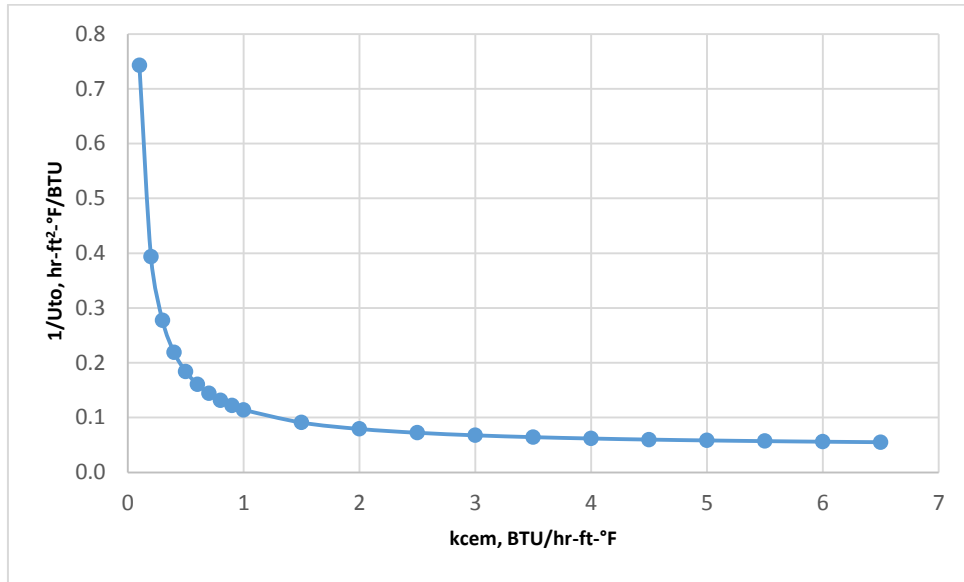


Figure 3 – Thermal resistance vs. cement thermal conductivity (Lower Wellbore Section)

The thermal conductivity of the cement and the overall thermal resistance of the wellbore are inversely proportional, and the decrease in resistance exhibits an exponential decline behavior initially, followed by a slow linear decline, which begins at approximately 3 BTU/hr-ft-°F (Figure 3).

The opposite is achieved when plotting the same cement thermal conductivities versus the overall heat transfer coefficient (Figure 4). This is due to the two values being directly proportional, so the overall heat transfer coefficient quickly increases to a certain value, after which it slowly increases in an almost-linear manner.

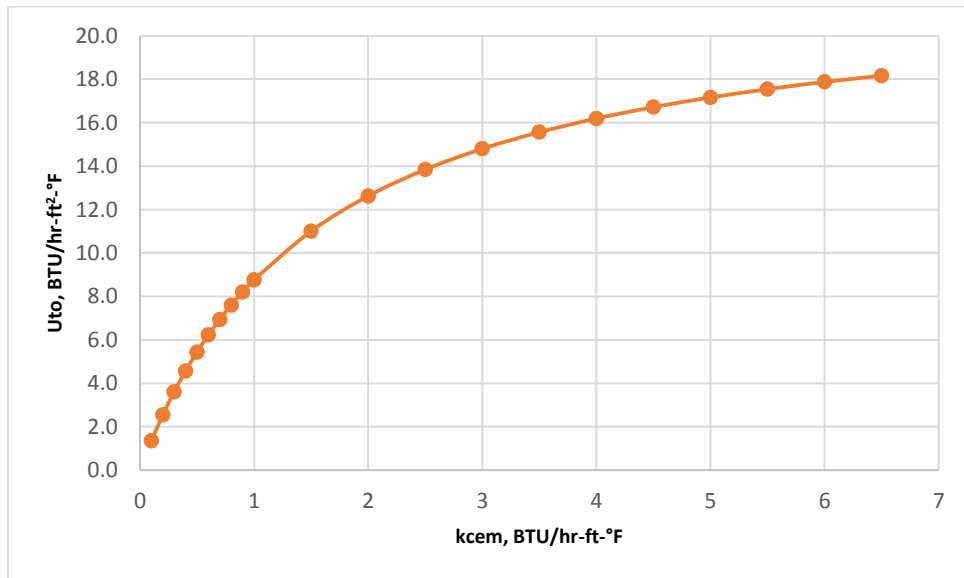


Figure 4 – Overall heat transfer coefficient vs. cement thermal conductivity (Lower Wellbore Section)

Figure 5 shows that by increasing the thermal conductivity from 0.1 to 3 BTU/hr-ft-°F, a 1000% increase of the heat exchange is achieved, whereas an increase of the cement conductivity from 3 to 6.5 BTU/hr-ft-°F yields a growth of the heat influx from the formation to the wellbore of approximately 23%. This means that the heat exchange, in this case, can only be controlled by changing the thermal properties of the cement up to a certain level, which could optimize the search for the best cement option when trying to maximize or minimize the heat exchange.

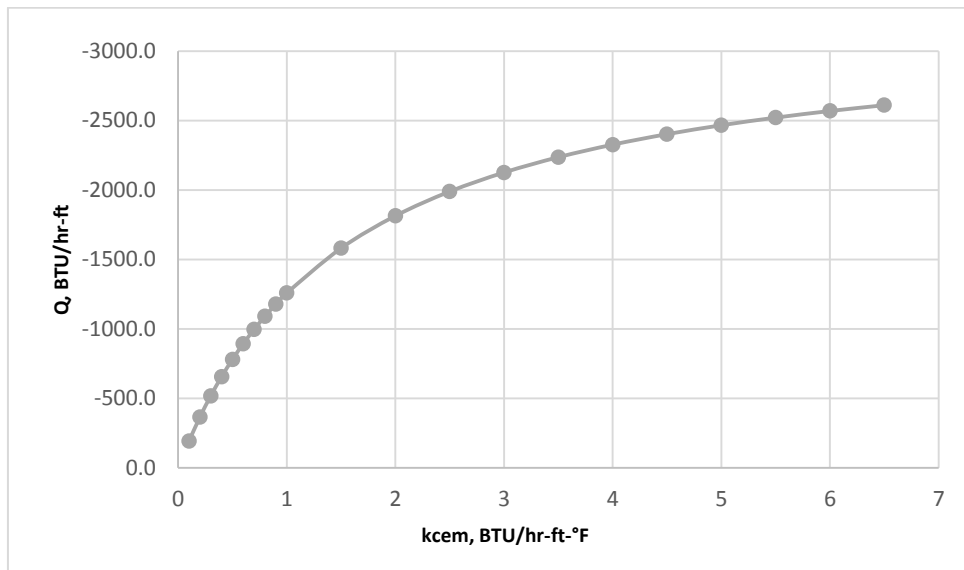


Figure 5 – Heat exchange vs. cement thermal conductivity (Lower Wellbore Section)

The same study was done for the upper wellbore section at a depth of 328 ft. (100m). A similar behavior of the parameters can be seen in **Figures 6 to 8**. However, in this case, the parameters have higher values and the heat exchange is positive, because of the negative temperature difference between the wellbore fluid and the formation.

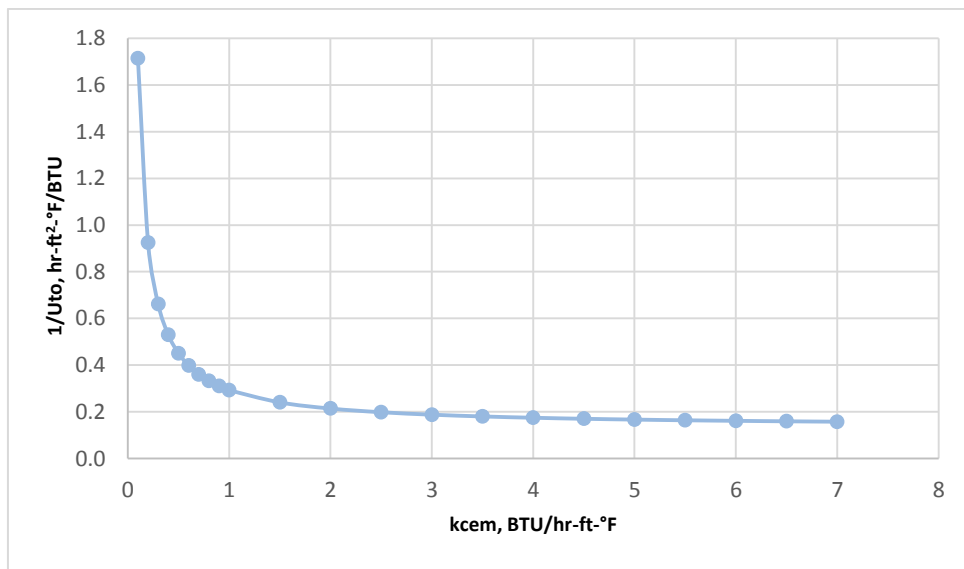


Figure 6 - Thermal resistance vs. cement thermal conductivity (Upper Wellbore Section)

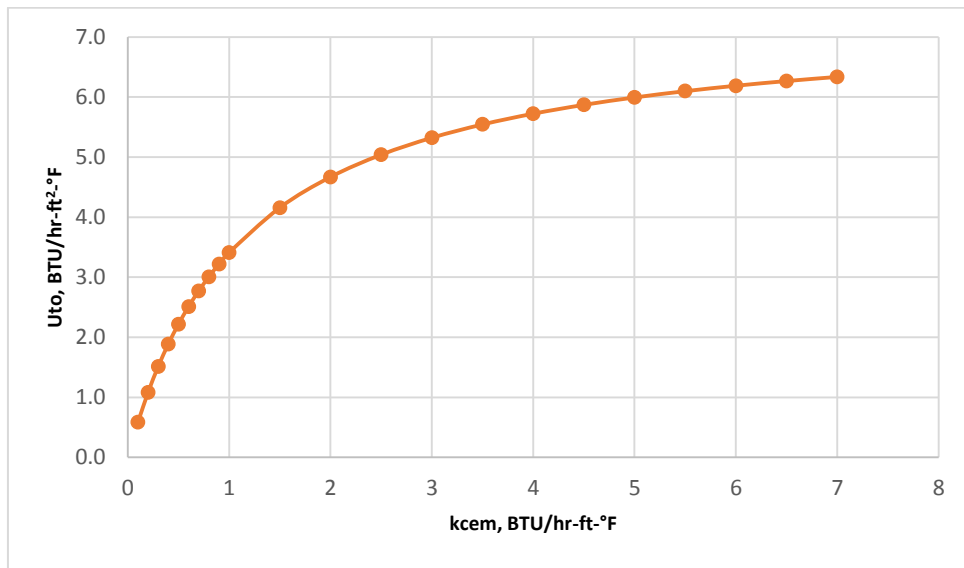


Figure 7 - Overall heat transfer coefficient vs. cement thermal conductivity (Upper Wellbore Section)

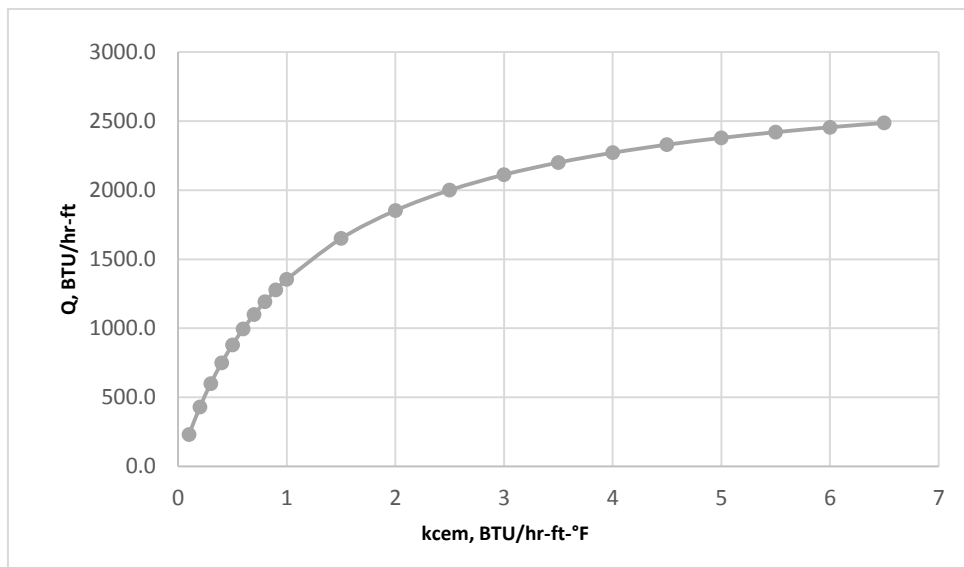


Figure 8 - Heat exchange vs. cement thermal conductivity (Upper Wellbore Section)

While increasing the contact area of the cement sheath with the reservoir, contrary to the expectations of Büchi (1990), a decrease in the heat exchange is observed. This can also be visualized in the following diagrams, which were plotted after changing the cement layer size (radius) while keeping the other wellbore components in the lower part of the reservoir unchanged. The cement layer radius is calculated by using **equation 5**:

$$r_{cemlayer} = r_{wb} - r_{co} \tag{5}$$

In other words, the wellbore radius is increased/decreased while the last casing size is kept constant in order to vary the cement layer radius. The bolded point on **Figures 9 to 11** represents the value corresponding to the initial wellbore radius.

Figure 9 shows a direct proportionality of the cement A layer size (blue line in **Figures 9 to 11**) and the overall resistance to heat exchange, which increases with the cement sheath radius. The reverse behavior is noticed when plotting the radius of the cement layer versus the overall heat exchange coefficient (**Figure 10**).

Due to the lower overall heat transfer coefficient and a higher resistance to heat exchange with the increasing radius of the standard cement (Cement System A), a drop in the heat exchange is observed, as presented in **Figure 11**.

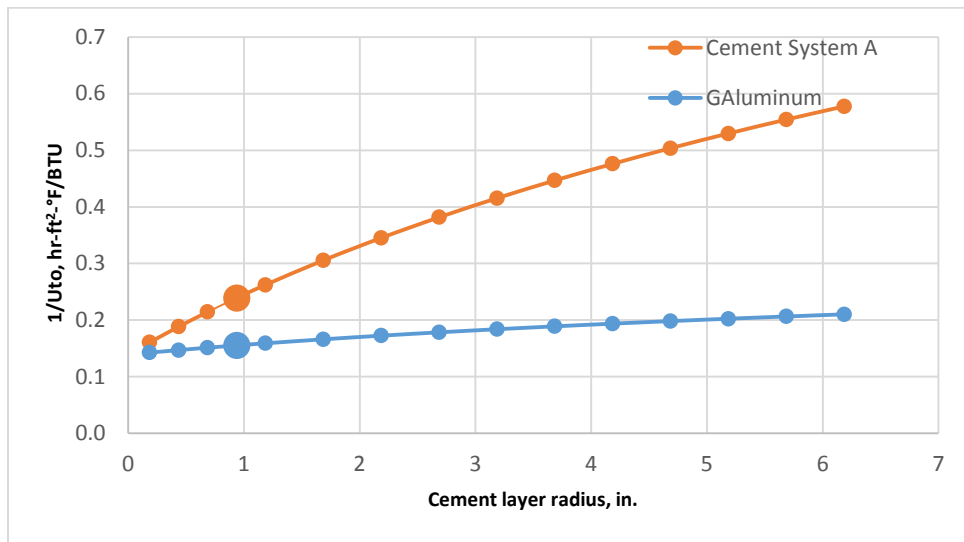


Figure 9 – Thermal resistance vs. cement layer radius (Lower Wellbore Section)

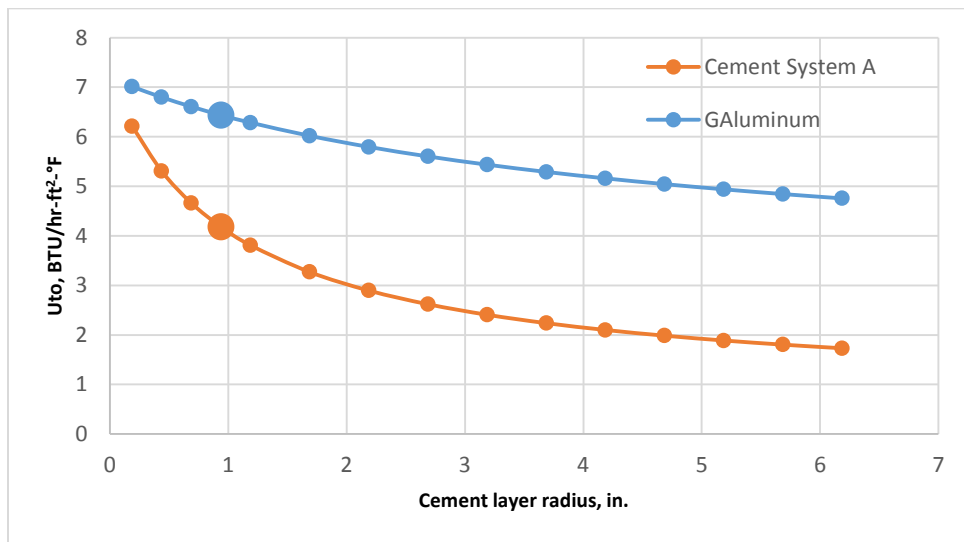


Figure 10 – Overall heat transfer coefficient vs. cement layer radius (Lower Wellbore Section)

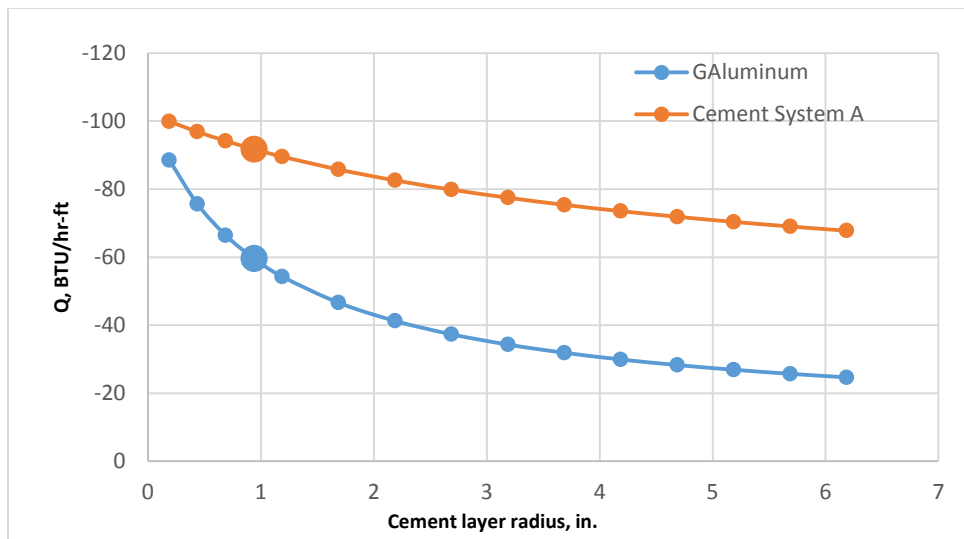


Figure 11 – Heat exchange vs. cement layer radius (Lower Wellbore Section)

In the case of a cement with a higher thermal conductivity (GAluminum – orange line in **Figures 9 to 11**), a slower increase of thermal resistance, together with a slower decrease of the overall heat transfer coefficient and heat exchange are observed, compared to the case of cement system A.

There is a 27% decrease of the unidirectional heat exchange to the wellbore after a 110% increase of the cement (GAluminum) layer size (from the initial 9½” wellbore size to 20”). In contrast, for the cement system A, a drop of 59% is observed for the same layer increase. This could be explained by the better capacity of the aluminum compound to store heat, which would make the GAluminum cement mixture more suitable for use as a heat buffer, instead of a heat flow enhancer.

2.5 Factors influencing the cement thermal conductivity

The importance of the cement thermal conductivity is clear when looking into the wellbore heat exchange of different sections of a wellbore. However, there is a paucity of data for this particular property, so it is predicted mathematically. The task of mathematical determination of thermal conductivities is complex and can be done in several different ways:

- Applying mixing laws for a rock-fluid system
- Using theoretical models, which are based on heat transfer mechanisms and simplified geometries
- Using empirical models, where adjustable parameters are defined for a set of materials via laboratory measurements.

Baghban *et al.* presented an interesting approach for the estimation of a settled cement’s thermal conductivity by using a three-phase model, incorporating cement, water and air. This concept, in which the porosity of settled cement and the fluids within the pores (water or air) are taken into account, is believed to be close to reality. The model, which is described by **equation 6**, can calculate the thermal conductivity of the hardened cement paste with pores filled by air and/or free water, and is an improvement over the existing two-phase series and parallel models presented by Somerton (1992).

$$k^n = m \cdot k_w^n + (\phi - m)k_a^n + (1 - \phi)k_s^n, \tag{6}$$

where the indices w, a and s stand for water, air and solid – hardened cement paste, ϕ represents the total porosity of the cement, m is the volume fraction of free water, and n represents an empirical correlation factor used to fit the model with experimental data in the best manner. Monte Carlo simulations of the thermal conductivity output show that, in the case of cement system B, **equation 6** is most sensitive to a variation in the total porosity of the hardened cement, which was assumed to be higher than 10% and lower than 51% (after Miranda *et al.*, 2010, and Alp *et al.*, 2013). In the 30,000 runs of the simulation, a standard deviation of 0.1 of the thermal conductivity of the hardened cement paste was assumed and the water content of the porosity randomly varied from 0 to the maximum porosity value for each step. The base value of the cement paste conductivity was 0.986 W/m-K and its variation was described by a normal distribution, whereas the other two parameters were described by a triangular distribution.

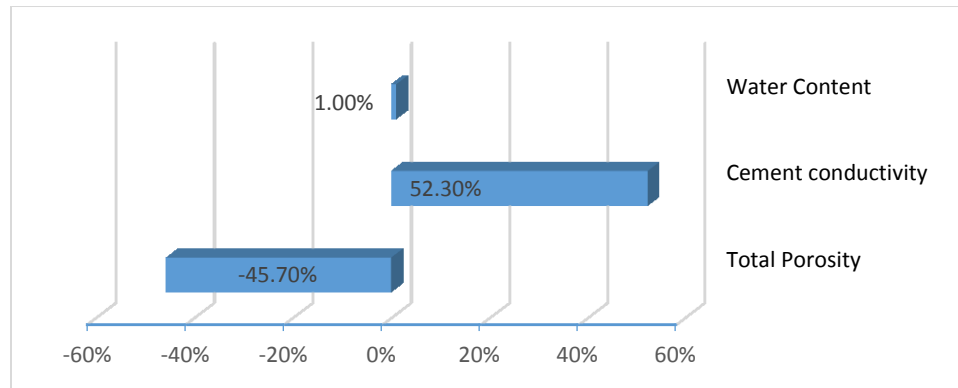


Figure 12 – Sensitivity analysis of the thermal conductivities

The simulation indicates a high probability that the calculated thermal conductivity of this specific composition is between 0.76 and 0.81 W/m-K, as showed in **Figure 13**.

By supposing that the presumed thermal conductivity of the cement is exact and only the cement porosity and its free water content are allowed to vary in the ensuing Monte Carlo simulation, a higher probability that the thermal conductivity of the three-phase system is in the same boundaries as in the previous case is observed. The same simulation also shows a general tendency of the cement system to have a higher thermal conductivity, explained by the fixed conductivity of the hardened cement paste (**Figure 14**).

The n-factor of the three-phase model was considered constant for these estimations (n=1). A separate simulation shows, however, the influence of the n correlation factor (**Figure 15**).

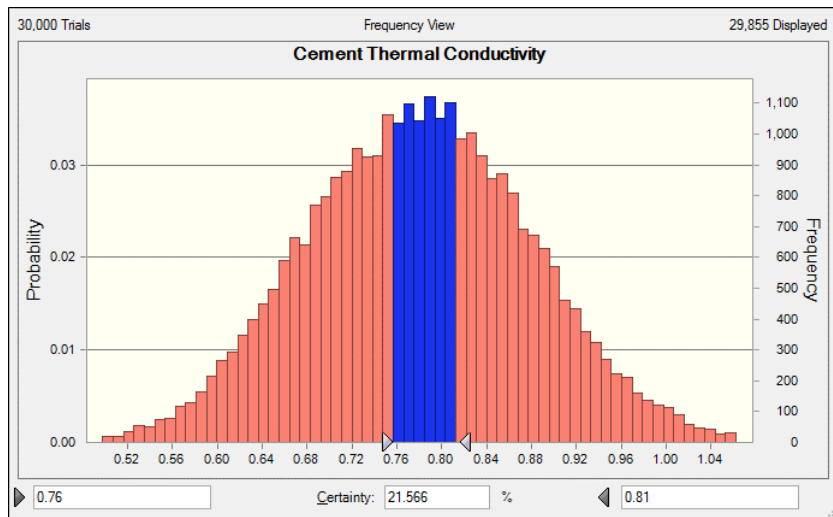


Figure 13 - Monte Carlo simulation #1 results- Cement B

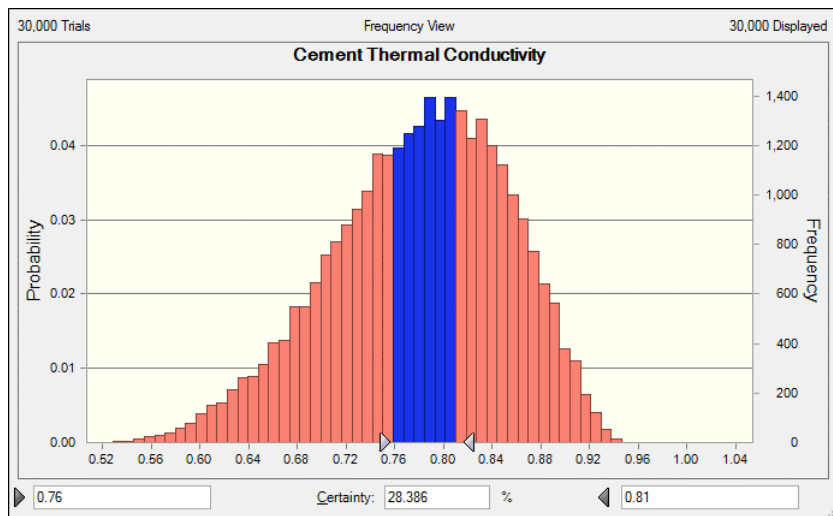


Figure 14 - Monte Carlo simulation #2 results- Cement B

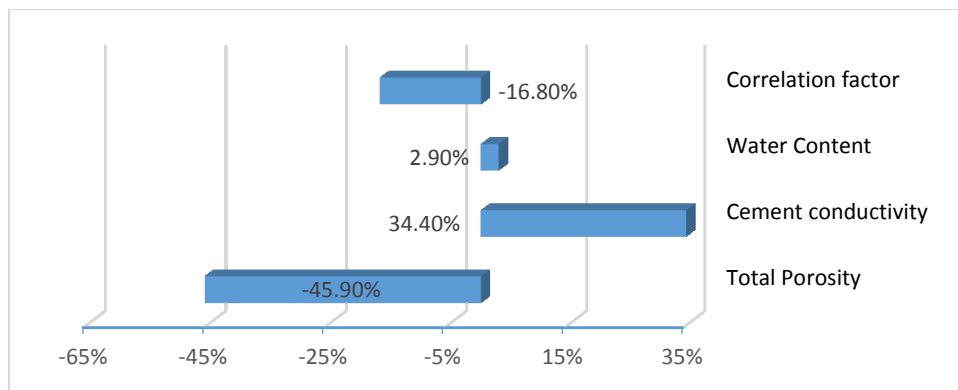


Figure 15 – Sensitivity analysis of the thermal conductivities including the n factor

3. CONCLUSIONS

Sensitivity studies evidenced that the heat exchange is sensitive to changes in the lower range of the cement thermal conductivity, with changes from up to a certain point not influencing the heat exchange in a strong manner.

It was shown that the heat exchange from the rock formation to the wellbore in the lower section of the well and the heat loss in the upper section of the wellbore can be maximized and minimized, respectively, by using the appropriate type of cement (conductive or insulating).

The size of the cement layer and that of the filter cake also play an important role in the entire wellbore heat exchange mechanism. A series of Monte Carlo simulations to investigate the influence different thermal and geometrical parameters in the accepted heat flow equations. By varying these parameters, after a certain point, an almost linear trend of the heat exchange was observed.

The combination of thermal conductivity estimation and computation of the heat exchange in the wellbore design affords the opportunity to directly compare cement components that provide similar heat exchange performance, and then select the most cost efficient option.

For the cement system A recipe, roughly one third API class H cement, one third silica flour, and one third water by volume, it is clear that a cement thermal conductivity of 2 – 3 BTU/hr-ft-°F works in an optimal way for the assumed wellbore configuration. Similar results are observed for the upper wellbore section case.

When looking into the size of the cement layer, the assessment of the heat exchange performance in different scenarios is even more effective. Operators can combine thermal conductivity and sizes of the cement layers in geothermal wells to see which approach is more capable of delivering a constant, high amount of heat at the wellbore. This, together with similar assessment of the heat storage capacity of the cement layers (recommended by the authors of this paper), can help maximize the thermal efficiency of future projects.

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