

The Effect of Filter Cake on the Heat Transfer in Geothermal Wellbores

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ABSTRACT

The drilling of deep wells requires the use of performance muds that can support and protect the wellbore during the process of 'making hole'. Before and during cement jobs, the goal is to remove as much as possible of the existing filter cake (a by-product of the drilling mud) in order to enhance the quality of the annular cement sheath. Experiments have shown that a thin filter cake often stubbornly remains between cement and formation, which is a cause for concern as the effectiveness of geothermal wells relies on maximizing the heat mining of the reservoir, and optimizing the heat transfer process is a major consideration. The effect of temperature on drilling fluids has undergone thorough investigations which show that high temperatures cause a degradation of rheological properties, as well as increasing fluid loss. In heat transfer estimations for geothermal well design, the required inputs relating to the drilling mud properties will be flawed, unless the filter cake is taken into account. This paper describes experimental investigations of filter cake thermal capacity and conduction, and subsequent theoretical estimation of the effect of filter cake on the wellbore heat transfer process. The results show that conventional water based muds can impair the heat transfer from and to the wellbore. Two mud samples were tested and it was observed that their thermal conductivities increased with temperature. It was noted that adding Barite to the drilling mud increased the thermal diffusivity of the filter cake, but it was found to be lower than that of the drilling fluid that produced it.

1. INTRODUCTION

The design of performance drilling fluids for geothermal wells presents a major challenge as temperatures and pressures encountered can be prohibitively high, so the cooling of these fluids and the need for stability and high thermal conductivity are vital if the heat transfer demands on these fluids are to be met (Sedaghatzadeh, 2012). The need to understand the thermal properties of the fluids in drilled wells cannot be over stressed as it leads to better assessment of the heat flow while producing.

Drilling fluids are a fundamental component in the drilling process as they ensure a secure and fast establishment of a borehole. The fluid stays in contact to the borehole wall during the whole process and generates a well protection barrier called filter cake, which is important for controlling fluid loss and wellbore stability. There is an interaction between the formation, the filter cake and the drilling fluid. One parameter which is influencing the drilling process is temperature. As heat affects the behavior of fluids, it is important to know about the rheological changes and the impact of temperature variation.

Better well design should result from improved knowledge of the temperature distribution of the circulating drilling fluids, the wellbore and the surrounding formation as transient thermal behavior during drilling and completion can be predicted more confidently (GARCÍA-GUTIÉRREZ et al., 2005). The anticipated improvements should be reflected in reduced well completion costs.

While rock properties are generally well characterized and data are plentiful, the thermal properties of drilling fluids and cements and how they behave under temperature variation are almost unknown. Through measurements, it is possible to gain data about several properties. This paper refers to experiments on the effect of the filter cake on the thermal exchange between the borehole wall and the fluid itself. The thermal diffusivity and heat capacity of two water-based drilling fluids (WBF) were measured in order to compute the thermal conductivity, and so provide a better understanding of the heat transfer between the formation and the drilling fluid. Results should improve the design of drilling programs for geothermal wells and may have potential for the oil and gas industry. Furthermore, the results show the importance of removing the filter cake and damage zone when heat mining is important.

2. FILTER CAKE THERMAL PROPERTIES AND THEIR MEASUREMENT

In order to reduce fluid loss, drilling fluids are designed to form a thin impermeable membrane at the drilling mud/borehole wall interface, which is commonly called filter cake. Good drilling muds will produce filter cakes with a thickness of less than 3 mm, but high temperature conditions may adversely influence the filter cake forming process, causing increased thickness and correspondingly higher mud losses. The following section describes the measurements performed on standard filter cakes, which were produced using an API filter press. The filter cakes were generated under low pressure conditions and room temperature.

2.1 Experimental investigations

Two substantial experimental investigations were carried out to measure heat capacity and thermal diffusivity. These experimentally determined properties were used to calculate the thermal conductivity.

2.1.1 Heat Capacity Measurement

Laboratory measurements of heat capacity were performed using the DSC module Q2000 from TA Instruments, see Figure 1 (TA Instruments 2007). The DSC method determines a changing enthalpy with the help of a calorimeter, which measures the rate of heat flow in comparison to a baseline. The baseline describes a situation where the heat flow does not influence the sample. The measurement instrument meets the DIN EN ISO 11357-1 engineer standards. Two measuring cells are heated on a metal plate according to the desired temperature program in a furnace. The DSC measures the heat rate of heat flow (\dot{Q}) which is the heat per time. The heating rate (v) serves as a proportionality factor. The following formula illustrates the connection between the heat capacity (c_V), rate of heat flow, the heating rate and mass:



Figure 1: Measured heat capacity of water compared to reference values

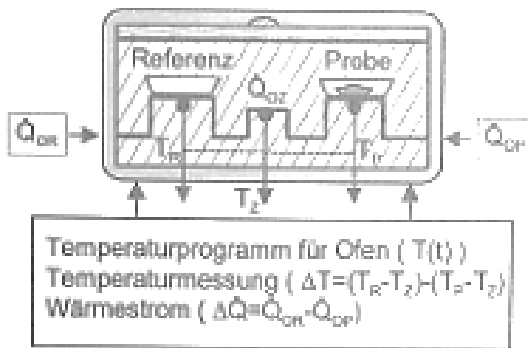


Figure 2: Measuring principle DSC (Ehrenstein, Ahlers-Hestermann 2004)

$$\frac{\dot{Q}}{m} = v * c_V$$

In the first instance, the heat capacity of water was determined and compared with reference values from the literature. Then, the heat capacity for the two drilling fluids and their filter cakes was measured. The following steps explain the measurement procedure:

- The weight of the sample and the measuring cell is set to be 10 g in total.
- A press encapsulates the measuring cell, so that the sample is hermetically sealed and no vapor from either the drilling fluid or the filter cake can escape from the cell.
- The measuring cell is introduced into the sample holder

- A second reference cell is prepared. Sapphire, with a heat capacity of 0.754 kJ/(kg*K) at 20°C, is used as the reference
- Software is used to adjust settings (type of cell, weight of sample) to the desired measurement conditions and temperature range.
- The automatic arm introduces the two samples to the furnace and the measurement starts with measuring the heat capacity of the desired drilling fluid, followed by calibration with a sapphire measurement.
- The measurement is repeated for other samples.

The obtained data using the DSC technique are presented in Figure 3 and Tables 1 and 2.

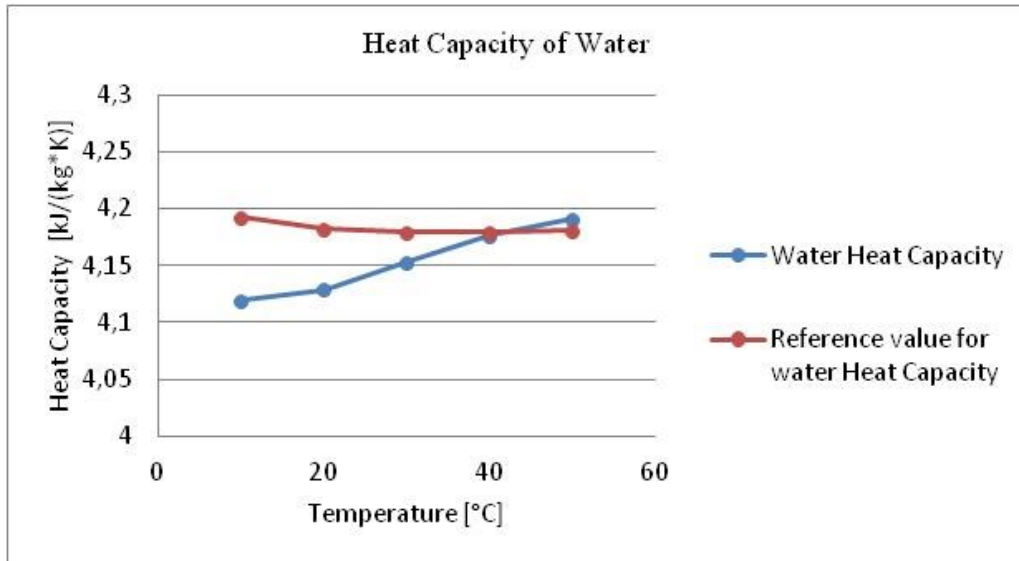


Figure 3: Measured heat capacity of water compared to reference values

Table 1: Measured heat capacity of water compared to reference values

Temperature [°C]	Measured heat capacity of water $[\frac{kJ}{(kg*K)}]$	Reference value of water heat capacity $[\frac{kJ}{(kg*K)}]$
10	4.120	4.192
20	4.129	4.182
30	4.153	4.179
40	4.176	4.179
50	4.192	4.181

Table 2: Measured heat capacity results for the drilling fluids and their filter cakes

Temperature [°C]	WBF + 6% Bentonite $[\frac{kJ}{(kg*K)}]$	Filter cake (Water + Bentonite) $[\frac{kJ}{(kg*K)}]$	WBF + Bentonite + Barite $[\frac{kJ}{(kg*K)}]$	Filter cake (Water + Bentonite + Barite) $[\frac{kJ}{(kg*K)}]$
10	3.854	3.724	1.946	1.654
20	3.854	3.714	1.975	1.658
30	3.866	3.717	2.008	1.673
40	3.869	3.714	2.042	1.676
50	3.870	3.726	2.073	1.685

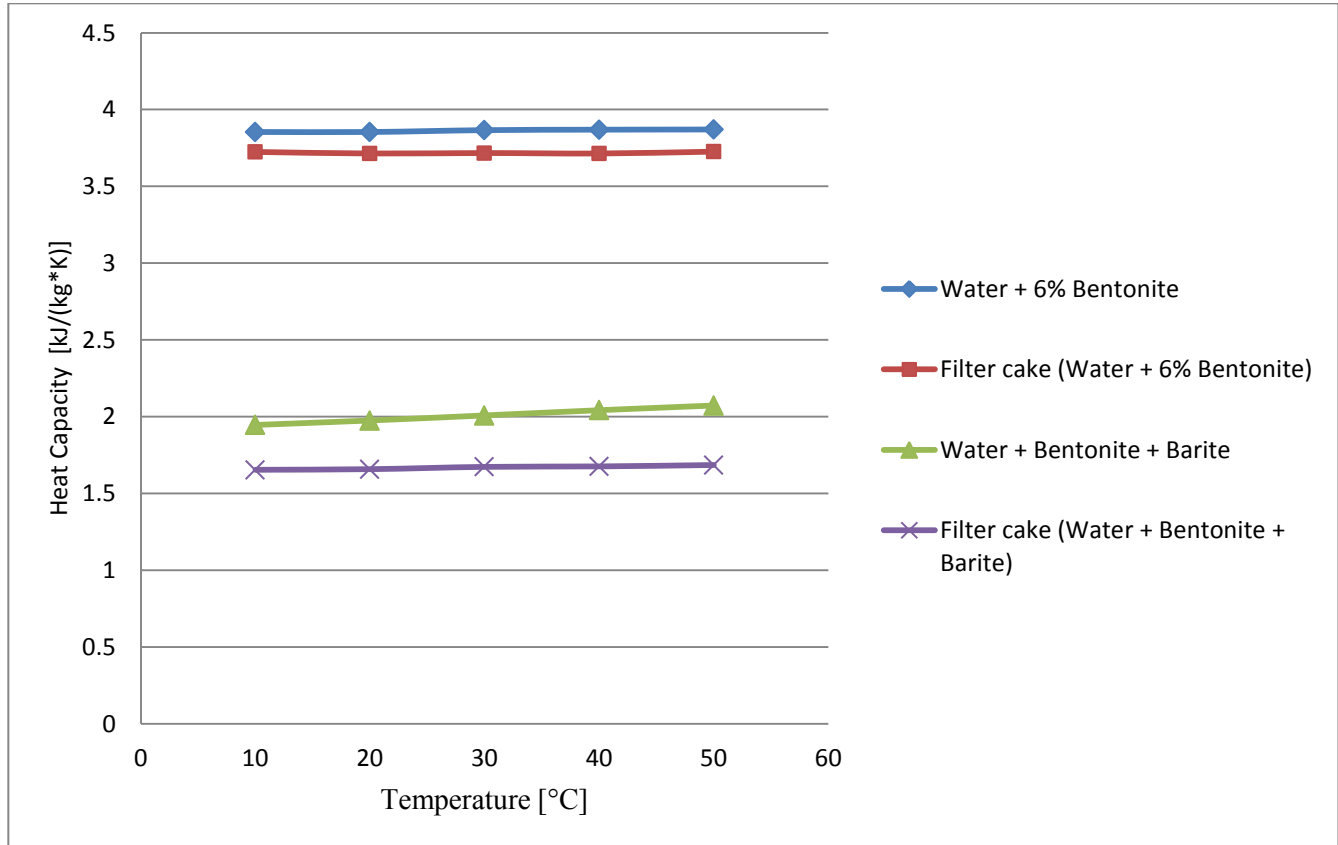


Figure 4: Measured heat capacity results for the drilling fluids and their filter cakes

2.1.2. Procedure for Thermal Diffusivity Measurement

The thermal diffusivity measurements for the drilling fluids and their filter cakes were performed using the Laser Flash Apparatus (LFA 427), which was provided by Netzsch GmbH & Co. Holding KG, see Figure 5. The LFA 427 is suitable for solid and liquid samples. The absolute accuracy for the measured thermal diffusivity is $\pm 5\%$ and the static error for three individual measurements is $\pm 2\%$ (DLR, 2014). Before the samples were tested, the measurement was run with water in order to compare the results with those from the literature. The measurement procedure consists of the following steps: the sample is introduced to the apparatus; then, a single laser pulse heats the sample from the bottom; the difference in temperature at the upper side of the sample is measured by a detector; a software program acquires the data and computes the thermal diffusivity (a). What matters is the thickness (l) of the given sample and the time to reach 50% of the maximum increase in temperature ($T_{0,5}$). Thermal diffusivity is derived from equation 1.

$$a = 0,1338 \cdot l^2 / T_{0,5} \quad (1)$$

The following steps explain the thermal diffusivity measurement of the fluids at different temperatures.

- The bottom and top of the sample holder are coated with graphite several times, until a homogenous graphite layer is established.
- The desired fluid is poured into the cup until a height of 1.0 mm is reached.
- The sample holder is closed and installed in the LFA 427.
- The furnace is put in place and the sample is isolated from the surroundings.
- Argon is injected as the experimental atmosphere.
- Experimental settings and temperature steps are adjusted.
- The measurement starts. The laser pulse heats the sample from the bottom three times for every temperature step to guarantee an unaffected result.
- The difference in temperature at the upper side of the sample is measured by a detector.
- The software program computes the thermal diffusivity.



Figure 5: Laser Flash Apparatus LFA 427 (Netzsch GmbH & Co. Holding KG)

The measurement of thermal diffusivity was performed for water, the two drilling fluids and their filter cakes. As a calibration, water was tested and compared to reference values of thermal diffusivity of local water samples reported in the literature, as shown in **Table 1**. The deviation is around 10% to 15% for the water measurement, and the values are consistently $0.02 \text{ mm}^2/\text{s}$ below those from the literature. This observation suggests that the measured thermal diffusivity values for the two drilling fluids and their filter cakes may also be around $0.02 \text{ mm}^2/\text{s}$ lower than their exact values.

The fluids and filter cakes were tested using a cup for Liquid Samples. A laser pulse of 700 V , a pulse width of 1.0 ms and the correction model of Cowan + Pulse (CCP) was chosen for the thermal diffusivity measurement. The CCP model is the most recommended model by the LFA manufacturer.

Tables 4 through 6 show the averaged measured values for two selected water based muds and their filter cakes. Figure 6 gives a graphical view of the thermal diffusivity as a function of temperature for a range of 20°C to 50°C . Barite will increase the thermal diffusivity of the filter cake much more comparing with mud. It looks like that the water high thermal capacity will hinder the barite effects in mud system, whereas in the filter cake the solids properties have a significant influence.

Table 3: Thermal diffusivity of water (20°C)

Laser shot number	Temperature [$^\circ\text{C}$]	Model	Thermal diffusivity [mm^2/s]	Reference value [mm^2/s] [29]
1	21.6	Cowan + Pulse Correction	0.122	0.1434
2	21.8	Cowan + Pulse Correction	0.122	0.1434
3	21.8	Cowan + Pulse Correction	0.108	0.1434
Average	21.7		0.117	0.1434
Standard deviation	0.1		0.008	0.0000

Table 4: Thermal diffusivity of WBF + 6% Bentonite

Temperature [$^\circ\text{C}$]	Thermal diffusivity of WBF + 6% Bentonite [mm^2/s]
22.6	0.131
29.9	0.147
39.5	0.162
49.5	0.174

Table 5: Thermal diffusivity of WBF + Bentonite + Barite

Temperature [°C]	Thermal diffusivity of WBF + Bentonite + Barite [mm ² /s]
22.2	0.143
30.2	0.141
39.5	0.153
49.7	0.188

Table 6: Thermal diffusivity of filter cake formed by WBF + Bentonite + Barite

Temperature [°C]	Thermal diffusivity of filter cake (WBF + Bentonite + Barite) [mm ² /s]
21.3	0.131
30.1	0.135
40.1	0.146
49.5	0.153

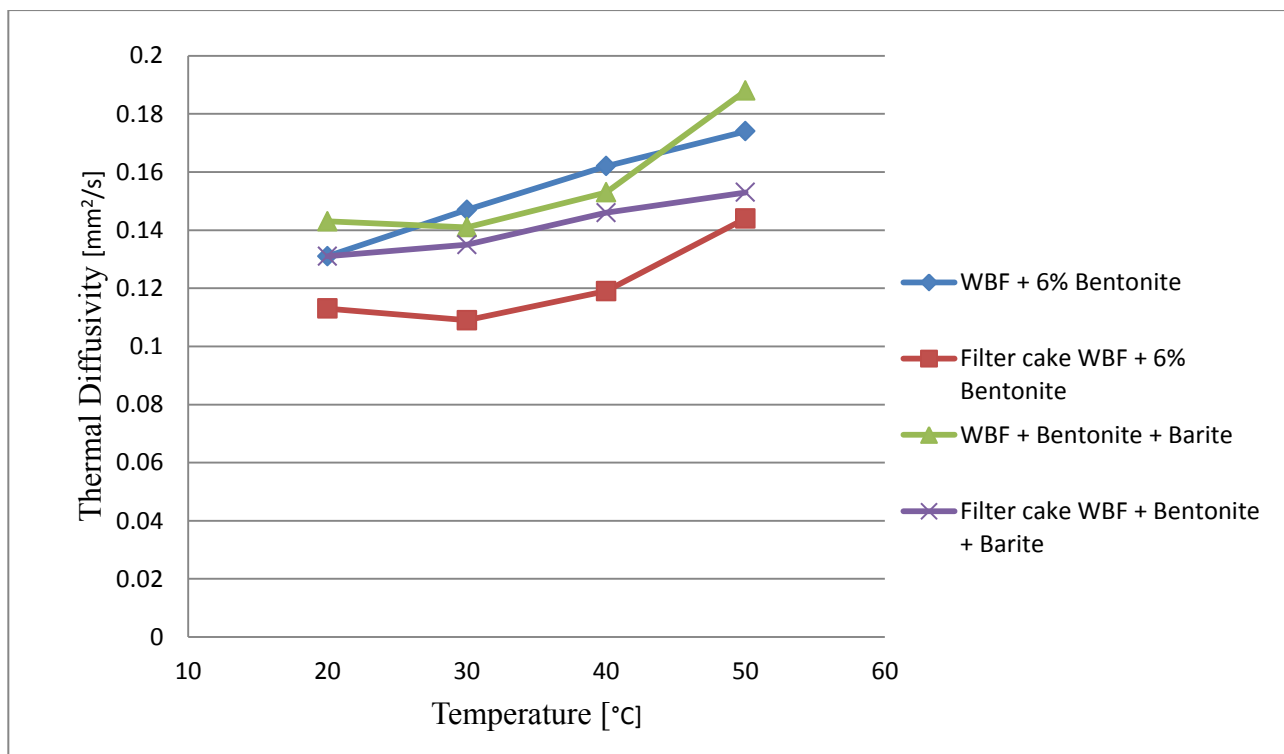


Figure 6: Measured thermal diffusivity of drilling fluids and their filter cakes

2.1.3. Thermal Conductivity Calculation

After measuring the density, heat capacity and the thermal diffusivity of the samples, it is possible to determine the thermal conductivity of the drilling fluids and their filter cakes by using equation 2 (DLR 2014),

$$\lambda(T) = a(T) * c_v(T) * \rho(T) \tag{2}$$

where: α is the thermal diffusivity as a function of temperature, c_v is the heat capacity as a function of temperature and ρ is the density as a function of temperature.

Table 7 and Table 8 illustrate the thermal conductivity of the WBF + 6% Bentonite and its filter cake, respectively. The results for the WBF + Bentonite + Barite and its filter cake are given in Table 9 and Table 10, respectively. The measured values are presented graphically in Figure 7. The heat conductivity vary significantly between water based mud and its filter cake, whereas the heat capacity for WBF with barite shows very little difference.

Table 7: Measured and calculated thermal properties of WBF + 6% Bentonite

WBF + 6% Bentonite				
Temperature [°C]	Density [$10^3 \left(\frac{kg}{m^3}\right)$]	Heat Capacity [$\frac{kJ}{(kg \cdot K)}$]	Thermal Diffusivity [$\frac{10^{-6}m^2}{s}$]	Thermal Conductivity [W/m·K]
20	1.0300	3.854	0.131	0.520
30	1.0273	3.866	0.147	0.584
40	1.0253	3.869	0.162	0.643
50	1.0250	3.870	0.174	0.690

Table 8: Measured and calculated thermal properties of filter cake formed by WBF + Bentonite

Filter cake (WBF + Bentonite)				
Temperature [°C]	Density [$10^3 \left(\frac{kg}{m^3}\right)$]	Heat Capacity [$\frac{kJ}{(kg \cdot K)}$]	Thermal Diffusivity [$\frac{10^{-6}m^2}{s}$]	Thermal Conductivity [W/m·K]
20	1.057	3.714	0.113	0.444
30	1.054	3.717	0.109	0.427
40	1.052	3.714	0.119	0.465
50	1.050	3.726	0.144	0.563

Table 9: Measured and calculated thermal properties of WBF + Bentonite + Barite

WBF + Bentonite + Barite				
Temperature [°C]	Density [$10^3 \left(\frac{kg}{m^3}\right)$]	Heat Capacity [$\frac{kJ}{(kg \cdot K)}$]	Thermal Diffusivity [$\frac{10^{-6}m^2}{s}$]	Thermal Conductivity [W/m·K]
20	1.590	1.9750	0.143	0.449
30	1.587	2.0080	0.141	0.449
40	1.583	2.0420	0.153	0.495
50	1.580	2.0725	0.188	0.616

Table 10: Measured and calculated thermal properties of filter cake formed by WBF + Bentonite + Barite

Filter cake (WBF + Bentonite)				
Temperature [°C]	Density [$10^3 \left(\frac{kg}{m^3}\right)$]	Heat Capacity [$\frac{kJ}{(kg \cdot K)}$]	Thermal Diffusivity [$\frac{10^{-6}m^2}{s}$]	Thermal Conductivity [W/m·K]
20	2.062	1.658	0.131	0.448
30	2.060	1.673	0.135	0.465
40	2.057	1.676	0.146	0.503
50	2.055	1.685	0.153	0.530

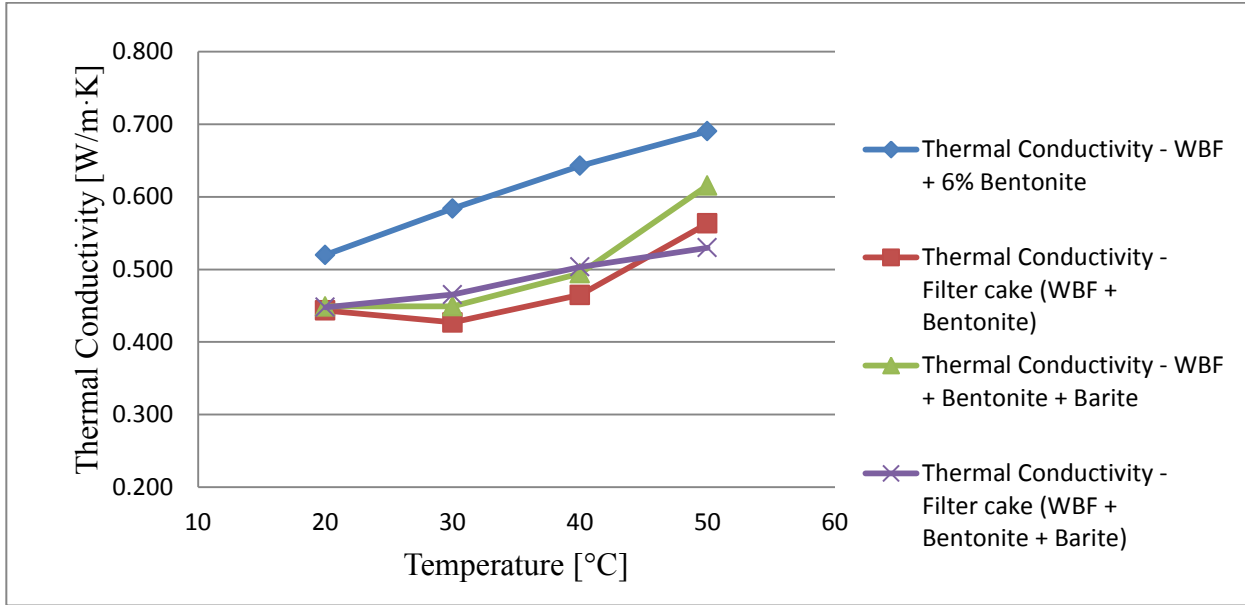


Figure 7: Calculated thermal conductivity vs. temperature

2.2 Using thermal properties of the filter cake

A simple calculation with one of the computed thermal conductivities shows the benefit of the measured values. Consider a cuboid, with a given cross section area ($A = 1.5 \text{ mm}^2$) and a given length ($l = \Delta x = 3 \text{ cm}$), it is possible to calculate the rate of heat flow through the cuboid.

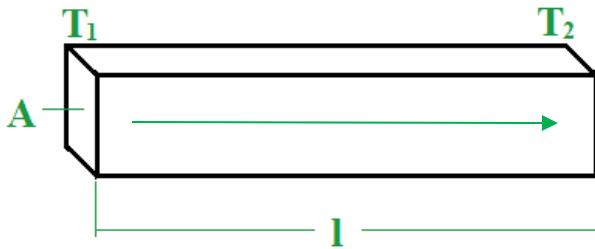


Figure 8: The cuboid used for the numerical example

The inlet end of the cuboid has the temperature $T_1 = 50^\circ\text{C} = 323.15 \text{ K}$, while at the outlet end of the cuboid, the temperature is $T_2 = 20^\circ\text{C} = 293.15 \text{ K}$. The cuboid consists of the WBF + 6% Bentonite mixture. For the thermal conductivity, the corrected value from Table 11 was used. At the outlet temperature of 20°C , the thermal conductivity (λ) is $0.625 \text{ W}/(\text{m}\cdot\text{K})$. Based on the computed thermal conductivity, it is possible to calculate the rate of heat flow through the cuboid. Using the thermal conductivity equation (Netzsch, 2014) the calculation was performed as follows:

$$\dot{Q} = \frac{dQ}{dt} = -\lambda A \frac{T_2 - T_1}{\Delta x} \quad (3)$$

$$\dot{Q} = \frac{1.5 \cdot 10^{-6} \text{ m}^2 \cdot 0.625 \frac{\text{W}}{\text{m}\cdot\text{K}} \cdot (323.15 - 293.15) \text{ K}}{0.03 \text{ m}} \quad (4)$$

$$\dot{Q} = 9.375 \cdot 10^{-4} \text{ W} \quad (5)$$

The calculated rate of heat flow is the transported energy in form of heat through the given cuboid. Furthermore, the values from the laboratory experiments can help to develop a formula or a program in order to determine the temperature distribution in the well.

The second case considers two cubes which are connected to each other, as shown in Figure 9. One cube is filled with sandstone at an inlet temperature of 50°C , the other cube is filled with the WBF + 6% Bentonite mixture at an outlet temperature of 20°C . External influences, such as the surrounding temperature, are not considered.

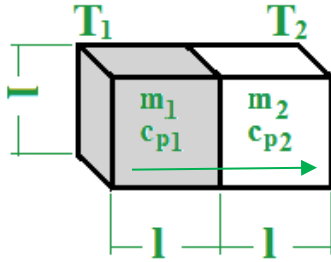


Figure 9: Two cube connected model used to investigate the effect of filter cake on heat transfer process

Heat will be exchanged from the hotter sandstone cube to the cooler cube containing the WBF + 6% Bentonite mixture. After a certain time, a thermal equilibrium will be attained, where both cubes will have the same temperature. With the help of the heat capacity and mass, it is possible to calculate this so called mixed temperature (T_m) using the mixing law in **Equation 6**:

$$T_m = \frac{m_1 \cdot c_{p1} \cdot T_1 + m_2 \cdot c_{p2} \cdot T_2}{m_1 \cdot c_{p1} + m_2 \cdot c_{p2}} \quad (6)$$

The data from the experiments and from the literature that are required to compute the mixed temperature are given in **Table 11**. Thus, it is possible to calculate the point at which the decreasing temperature of the sandstone cube and the increasing temperature of the WBF + 6% Bentonite cube are in balance.

Table 11: Values used in the two cube connected model for the calculation of the mixed temperature

Sample	Temperature [°C]	Volume Cube [m ³]	Density ρ [kg/m ³]	Heat capacity (c_p) [J/(kg·K)]
WBF + 6% Bentonite	20	0.001	1.03	3854
Sandstone (Ichim, 2015)	50	0.001	2.15	710

The resultant mixed temperature is 29°C. Due to the relative heat capacities, the WBF was able to cool the sandstone down by 20°C, while the drilling fluid was heated up by 9°C. This confirms that water-based drilling fluid is a good cooling medium. In the experimental section of this paper, it is possible to see that the measurement results for the thermal conductivity are quite low in comparison to the thermal conductivity of solid samples. This stresses the argument that water is suitable for cooling processes, too.

3. CASE STUDY ON THE EFFECT OF FILTER CAKE ON THE OVERALL HEAT TRANSFER COEFFICIENT

Ichim (2015) provides detailed calculation methodology for the simulated heat exchange of a geothermal production well (**Figure 10**), at an assumed depth of 14,000 ft. The temperature difference between the produced fluid and the formation is taken as 40 °C, and the fluid inside the production casing has an assumed thermal conductivity of 0.604 W/m·K. This value is equal to the thermal conductivity of water at surface temperature, and was used for reasons of simplicity. The overall heat exchange coefficient for this section of the well is calculated using Equation 6; the one-dimensional heat exchange per unit length of wellbore is calculated for different cement systems according to Equation 5; using properties given in Table 12. Again, for simplicity, heat transfer by convection is neglected.

Under steady state conditions, the rate of heat flow through the wellbore per unit of length is, according to Hasan and Kabir (2002):

$$Q = -2\pi \cdot r_{to} \cdot U_{to} (T_f - T_{wb}) \quad (7)$$

Where U_{to} represents the overall heat transfer coefficient, $(T_f - T_{wb})$ the temperature difference between the wellbore/formation interface and the wellbore fluid and $2\pi \cdot r_{to}$ the tubing outside area.

$$\frac{1}{U_{to}} = \frac{r_{to}}{r_{ti} h_L} + \frac{r_{to} \ln(\frac{r_{to}}{r_{ti}})}{k_t} + \frac{r_{to} \ln(\frac{r_{ins}}{r_{to}})}{k_{ins}} + \frac{r_{to}}{r_{ins} (h_c + h_r)} + \frac{r_{to} \ln(\frac{r_{co}}{r_{ci}})}{k_c} + \frac{r_{to} \ln(\frac{r_{wb}}{r_{co}})}{k_{cem}} \quad (8)$$

Where r_{to} , r_{ti} , r_{ins} , r_{ci} , r_{co} , r_{wb} being the tubing outer radius, tubing inner radius, insulation radius, casing inner radius, casing outer radius and the wellbore radius, respectively; and h_L , h_c , h_r , k_t , k_c , k_{cem} are the liquid convective heat transfer coefficient, convective heat transfer coefficient, radiation heat transfer coefficient, conductivity of tubing material, conductivity of casing material, and the conductivity of the cement, respectively.

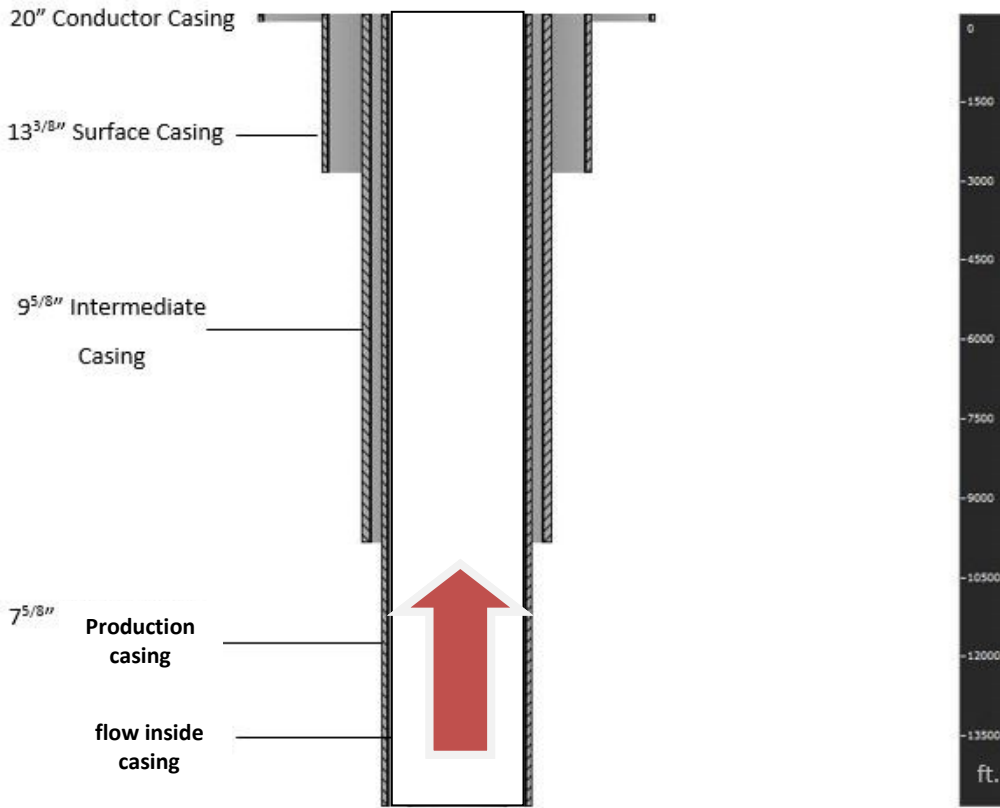


Figure 10: Wellbore profile (made with Halliburton’s eRedBook software)

It might also be of interest to understand the influence of the filter cake on the unidirectional heat exchange. For this purpose, Equation 8 is adapted as:

$$\frac{1}{U_{to}} = \frac{r_{to}}{r_{ti}h_L} + \frac{r_{to} \ln\left(\frac{r_{to}}{r_{ti}}\right)}{k_t} + \frac{r_{to} \ln\left(\frac{r_{ins}}{r_{to}}\right)}{k_{ins}} + \frac{r_{to}}{r_{ins}(h_c+h_r)} + \frac{r_{to} \ln\left(\frac{r_{co}}{r_{ci}}\right)}{k_c} + \frac{r_{to} \ln\left(\frac{r_{wb}}{r_{co}}\right)}{k_{cem}} + \frac{r_{to} \ln\left(\frac{r_{wbf}}{r_{wb}}\right)}{k_{mudfilter}} \quad (9)$$

r_{wbf} is the wellbore radius r_{wb} plus the filter cake thickness and $k_{mudfilter}$ is the thermal conductivity of the drilling mud filter cake, as determined by Romanowski (2015).

Table 12: Thermal conductivities of different wellbore materials (after Romanowski, 2015, Urazgaliyeva 2015, Ichim, 2015)

Material	Thermal conductivity, W/K-m
Steel	45
Formation	2.5
Cement	0.86 to 12.5
Drilling fluid	0.69
Filter cake (type)	0.17(1), 0.35(2), 0.563(3)

Two scenarios are simulated and the outcomes are shown in Figure 11 and Figure 12. Figure 11 shows the effect of filter cake thermal conductivity considering a constant filter cake thickness for all three filter cake types. The simulation shows that a low thermal conductivity filter cake can change the overall heat transfer coefficient by up to 25%, in other words, reducing the heat flow from the reservoir accordingly. Figure 12 shows that a change in thickness of the filter cake will not strongly affect the overall heat transfer coefficient (less than 5%). In reality, the temperature degradation of the drilling mud will increase the filter cake thickness and the equivalent formation damaged zone, but the water loss will create a much diluted filter cake with the benefit of higher thermal

conductivity. Numerical simulations have shown that, in deep wells, the filter cake thickness can reach values of up to 75 mm in some extreme cases, and 1 mm to 15 mm for optimized drilling (Kabir and Gamwo, 2011). Prior to cementing, filter cake is generally eroded or mechanically removed, but this process has never been experimentally investigated at elevated temperatures, therefore more research needs to be spent in this area.

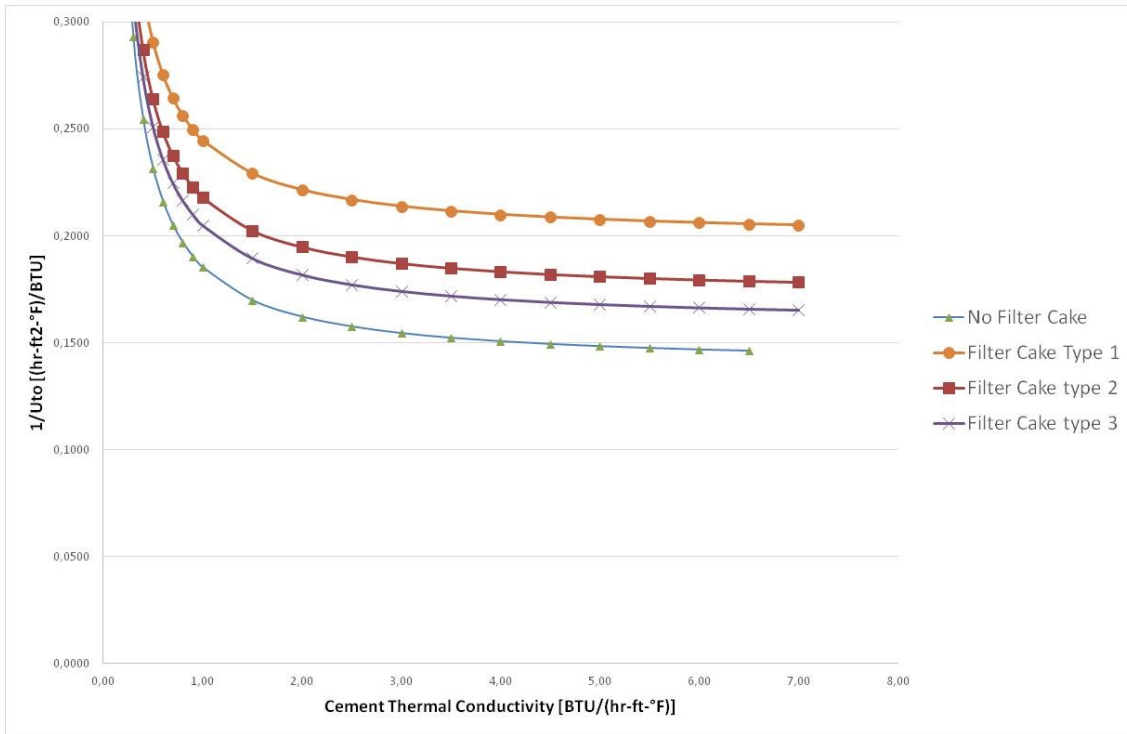


Figure 11: The effect of filter cake thermal properties on the overall heat transfer coefficient (Filter cake thermal conductivity for type 1 = 0.17, type 2 = 0.35, type 3 = 0.563)

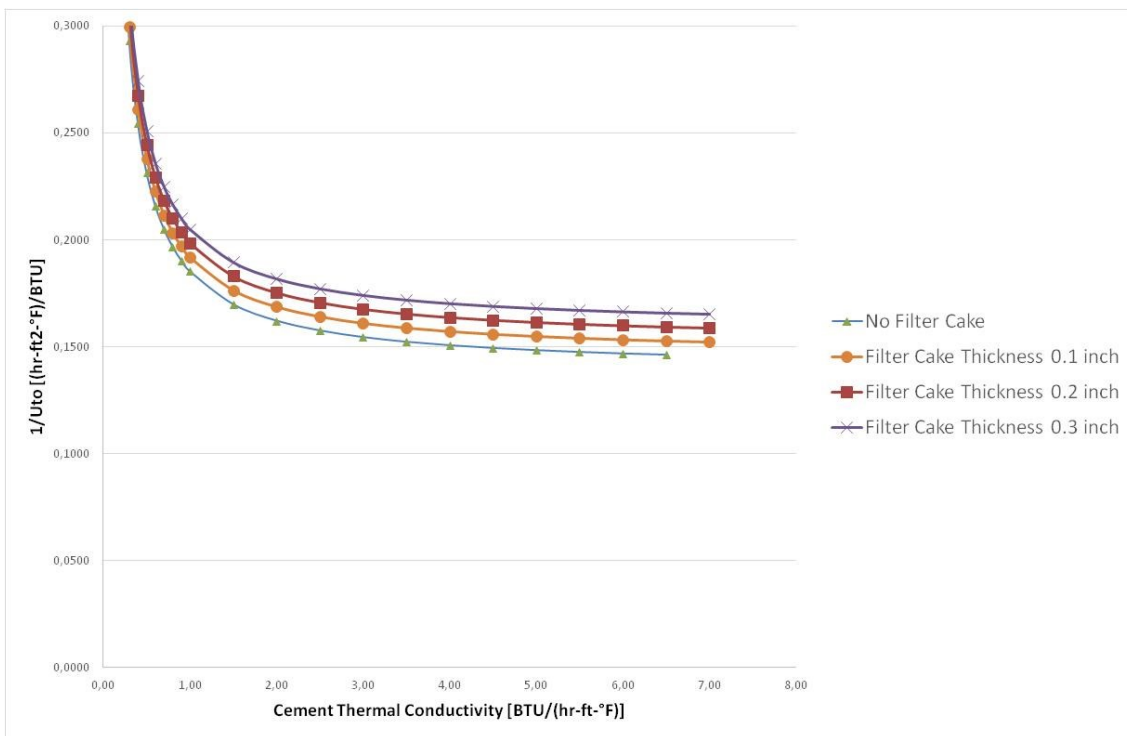


Figure 12: The effect of filter cake thickness on the overall heat transfer coefficient

4. CONCLUSIONS

The thermal properties of the filter cake formed by two different water based drilling muds have been investigated. The focus of this paper was to measure the heat capacity, heat diffusivity, and thermal conductivity of the filter cake.

It was found out that the filter cake can increase the overall heat transfer coefficient into the wellbore by up to 25%. This finding was for low conductivity filter cake, which is formed when barite, for example, is added to the mud.

As a result of this study, it is clear that the complete removal of the filter cake from the wellbore is not only important only for the quality of the cement job, but also to enhance the heat transfer into geothermal wells.

Although it was not directly investigated in this paper, the filter cakes that may form inside the fractures when hydraulically fracturing geothermal wells can also reduce the heat transfer.

Regarding future work, the investigation of the thermal properties of various drilling muds obtained under high pressure, high temperature (HPHT) conditions is proposed.

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