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CEMENTING OF GEOTHERMAL WELLS – RADIUS OF THERMAL INFLUENCE

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ABSTRACT

Temperature and pressure are two basic influences on the downhole performance of cement slurries. They affect how long the slurry will pump and how it develops the strength necessary to support the pipe. Temperature has the more pronounced influence. The downhole temperature controls the pace of chemical reactions during cement hydration resulting in cement setting and strength development. The shut-in temperature affects how long the slurry will pump and how well it develops. Assessment of the temperature development during hydration is necessary to determine how fast the cement will reach an acceptable compressive strength before the casing can be released. Cementing of casing of geothermal wells is conducted at high downhole temperatures. For this reason cement hydration retarders are often used. Thus is very important to predict the temperature increase during the cement setting. This will enable to determine the optimal time lapse between cementing and temperature survey. A semi-analytical formula which allow one to estimate the temperature increase versus setting time is used to describe the transient temperature at the cylinder's wall, while at the surface of the cylinder the radial heat flow rate (into formations) is a quadratic function of time. In order to more closely test the mechanical properties of cement under well conditions, the cement must typically be cured or hydrated for the appropriate amount of time under the temperature and pressure conditions as close as possible to downhole conditions in the well. At laboratory tests of cement slurries it is important to specify the radius of thermal influence. This will permit to determine the distance from the axis of the wellbore's model where a constant temperature should be maintained. The abovementioned formula is also used to estimate the radius of thermal influence. An example of calculations is presented.

INTRODUCTION

For deep and hot wells the heat generation during cement hydration may cause a substantial temperature increase in the annulus. This factor must be taken into account in cement slurry design. Temperature and pressure are two basic influences on the downhole performance of cement slurries. They affect how long the slurry will pump and how it develops the strength necessary to support the pipe. Temperature has the more pronounced influence.

The downhole temperature controls the pace of chemical reactions during cement hydration resulting in cement setting and strength development. The shut-in temperature affects how long the slurry will pump and how well it develops the strength to support the pipe. As the formation temperature increases, the cement slurry hydrates and sets faster and develops strength more rapidly. Cement slurries must be designed with sufficient pumping time to provide safe placement in the well. At the same time the cement slurry cannot be overly retarded as this will prevent the development of satisfactory compressive strength. To reduce the wait on cement we recommend increasing the outlet mud temperature. Earlier we suggested this technique to reduce wait on cement at surface casing for wells in permafrost regions (Kutasov, 1999). This may reduce the cost associated with cementing of the conductor and surface casing. The laboratory and field data show that the maximum value of heat production rate occurs during the first 5 to 24 hours. During this period the maximum temperature increase (ΔT_{max}) can be observed in the annulus. In order to evaluate the temperature increase during cement hydration it is necessary to approximate the heat production rate versus time curve by some analytical function $q = f(t)$. At laboratory tests of cement slurries it is important to specify the radius of thermal influence (physical "infinity"). This will enable to determine

the distance from the axis of the wellbore's model where a constant temperature should be maintained. A semi-analytical formula (Kutasov, 2007) was used to estimate the radius of thermal influence.

RATE OF HEAT GENERATION VERSUS TIME

When cement is mixed with water, an exothermic reaction occurs and a significant amount of heat is produced. This amount of heat depends mainly on the fineness and chemical composition of the cement, additives, and ambient temperature. As in any exothermic reaction, the rate of heat generation during cement hydration increases with the increase of the ambient temperature. It was observed that a quadratic equation can be used for short intervals of time to approximate the rate of heat generation (q) per unit of length as a function of time (Kutasov, 1999; Romero and Loizzo, 2000; Dillenbeck et al., 2002). Then

$$q = \pi(r_w^2 - r_c^2)\rho_c q_r q_D \qquad (1)$$

and

$$q_D = a_o + a_1 t + a_2 t^2, \qquad (2)$$

Where r_w is the well radius, r_c is the outside radius of casing, ρ_c is the density of cement, q_r is the reference rate of heat generation per unit of mass, q_D is the dimensionless rate of heat generation, and a_o, a_1, a_2 are coefficients. The reference rate of heat generation per unit of mass is an arbitrary parameter and, for simplicity, we can assume that, for example, for two curves in (Fig. 1) q_r = 1 mW/g. We will call the two curves as Ro77 and Ro122

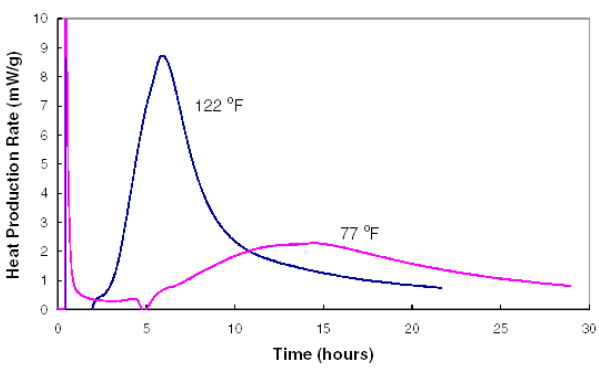

Fig. 1. Heat production rate per unit of mass as a function of time for class "*G*" neat cement at two temperatures (Romero and Loizzo, 2000)

The Eq. 1 can be presented in the following form,

$$q = A_o q_D, \qquad (3)$$

$$A_o = \pi\left(r_w^2 - r_c^2\right)\rho_c q_r. \qquad (4)$$

where A_o is the reference rate of heat generation per unit of length. In this case the values of heat flow rates per unit of mass will be numerically *equal* to its dimensionless values. When the table rate of heat generation versus time is available, then to obtain coefficients a_o, a_1, and a_2, a quadratic regression program can be used.

TEMPERATURE INCREASE AT CEMENT HYDRATION

Temperature surveys following the cementing operation are used for locating the top of the cement column behind casing. Field experience shows that in some cases the temperature anomalies caused by the heat of cement hydration can be very substantial. However, even in such cases it is very important to predict the temperature increase during the cement setting. This will enable to determine the optimal time lapse between cementing and temperature survey. Below we present a semi-analytical formula which will enables to estimate the temperature increase versus setting time (Kutasov, 2007). This formula describes the transient temperature at the cylinder's wall (T_v), while at the surface of the cylinder the radial heat flow rate (into formations) is a quadratic function of time:

$$\Delta T = T_V(t) - T_i = \frac{A_o}{2\pi\lambda}\left[a_o G_o(t) + a_1 G_1(t) + a_2 G_2(t)\right], \qquad (5)$$

$$G_o(t) = \ln\frac{\left(b + 2d\sqrt{t}\right)^2}{b(b + d\sqrt{t})},$$

$$\left\{\begin{aligned} &G_1(t) = -\ln(b)\left(t + \frac{B}{2}\right) - \frac{1}{2}t + \\ &\ln\left(b + 2d\sqrt{t}\right)\left(2t - \frac{B}{2}\right) + \ln\left(b + d\sqrt{t}\right)(B - t) \end{aligned}\right\},$$

$$\left\{\begin{aligned} &G_2(t) = -\ln(b)\left(t^2 - \frac{7}{8}B^2 + Bt\right) - \\ &\frac{1}{4}\left(3t^2 + Bt\right) + \frac{3}{4}B\sqrt{Bt} + \ln\left(b + 2d\sqrt{t}\right)\left(2t^2 + \frac{1}{8}B^2 - Bt\right) - \\ &\ln\left(b + d\sqrt{t}\right)(t - B)^2 \end{aligned}\right\},$$

$$b = 2.6691, \quad d = \frac{\sqrt{a}}{r_w}, \quad B = \frac{b^2}{d^2},$$

$$t = t^* - t_o.$$

Where T_i is the initial temperature of formations, a is the thermal diffusivity of formations, λ is the thermal conductivity of formations, t^* is the time since

cement slurry placement, t_o is the time interval due to cement retardation. Thus the cement hydration starts at $t = 0$.

EXAMPLE OF CALCULATIONS

A temperature survey was conducted to locate the top of the cement column behind casing. The rate of heat generation is presented in Fig. 1 (Curve Ro77). The surrounding wellbore formation is sandstone: Thermal conductivity is assumed as 1.9 kcal/(m·hr ·°C), thermal diffusivity - 0.0034m^2/hr. What are the values of temperature increase ΔT during cement hydration? The input parameters are: The bit diameter is 8.5 in, the outside diameter of casing is 3.5 in, density of cement (ρ_{cem}) is 15.8 ppg, q_r =,1 mW/g, A_o=Kcal/m·hr, $t_o \approx 5$ hours (from the plot, Fig. 1). To conduct calculations after Formula (5) it is necessary to approximate the sections of the $q = q(t)$ curves by a quadratic equation. For this reason tables of q versus t are needed. However, only plot of $q = q(t)$ is available. To digitize plot and obtain numerical values of q_D and time we used the *Grapher* software. To obtain the coefficients a_o, a_1, a_2, a quadratic regression program was used. We obtained for $3.0 \le t \le 16.2$ hr:

$$a_o = 0.2211, \quad a_1 = 0.4296 hr^{-1},$$

$$a_2 = -0.0228 hr^{-2}$$

The average squared deviation in approximation values of q by a quadratic equation is 4.09 %. The results of calculations are presented in Fig. 2. It is interesting to note that the maximum values of the temperature increase and the dimensionless heat flow rate do not coincide in time.

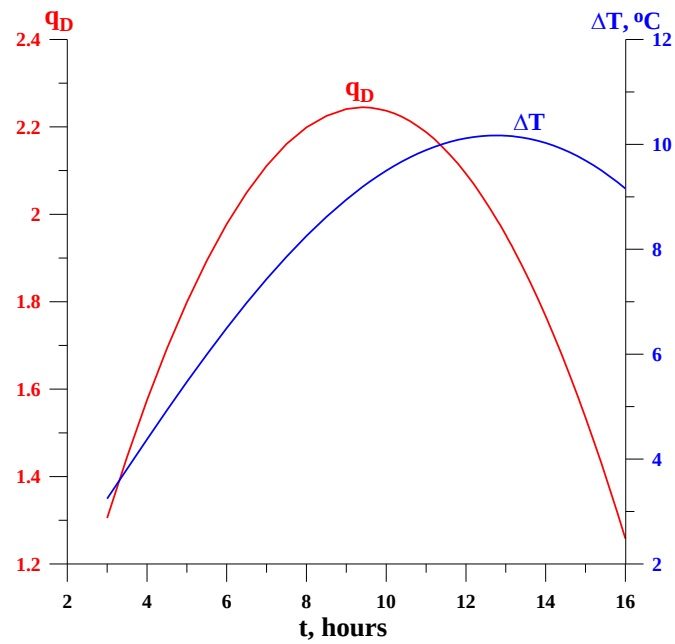

Fig. 2. The temperature increase during cement hydration: (Curve Ro77)

RADIUS OF THERMAL INFLUENCE AS CEMENTING

Earlier we used the thermal balance method to calculate the radius of thermal influence (r_{in}) as a function of time during drilling (Kutasov, 1999). Similarly, we will use the thermal balance method to evaluate the value of r_{in} for the cement hydration period. This parameter will allow estimating the degree of thermal disturbance created by the heat of the cement hydration. We found (Kutasov, 1999) that the dimensionless temperature distribution around the wellbore during drilling fluid circulation can be approximated by the following equation

$$\left\{ \begin{array}{l} T_D(r_D, t_D) = \dfrac{T(r,t) - T_f}{T_w - T_f} = 1 - \dfrac{\ln r_D}{\ln R_{in}}, \\ R_{in} = \dfrac{r_{in}}{r_w}, \quad r_D = \dfrac{r}{r_w}, \quad 1 \le r_D < R_{in} \end{array} \right\}, \quad (6)$$

$$t_D = \frac{at}{r_w^2} = \frac{\lambda t}{c_p \rho r_w^2} \ . \quad (7)$$

and the dimensionless cumulative heat flow rate from the wellbore per unit of length (Q_D) was evaluated

$$Q_D = \frac{1}{4} \frac{R_{in}^2 - 2\ln(R_{in}) - 1}{\ln(R_{in})} \ . \quad (8)$$

As we mentioned above we obtained a semi-analytical equation (5) which describes the borehole wall temperature when the borehole is cylindrical source with a quadratic function of the heat flow rate per unit of length.

$$q(t) = A_o\left(a_o + a_1 t \ + a_2 t^2\right), \qquad (9)$$

where A_o is the reference heat flow rate per unit of length. The cumulative heat flow per unit of length is

$$Q(t) = \int_0^t q(t)\, dt = q_o t\left(a_o + a_1 t/2 \ + a_2 \frac{t^2}{3}\right). \qquad (10)$$

The cumulative heat flow per unit of length can also be expressed by as

$$Q = 2\pi\rho c_p r_w^2\left(T_v - T_f\right)Q_D\,. \qquad (11)$$

Combining Eqs. (5), (7), (8), (10), and (11) we obtain an equation to determine the value of R_{in}

$$\frac{R_{in}^2 - 2\ln(R_{in}) - 1}{4\ln(R_{in})} \cdot \frac{a_o G_o + a_1 G_1 + a_2 G_2}{a_o + \frac{a_1}{2}t + \frac{a_2}{3}t^2} = t_D \qquad (12)$$

We used the last formula and obtained coefficients a_o, a_1 and a_2 to compute the dimensionless radius of thermal influence for the well Ro77 (Fig. 3).

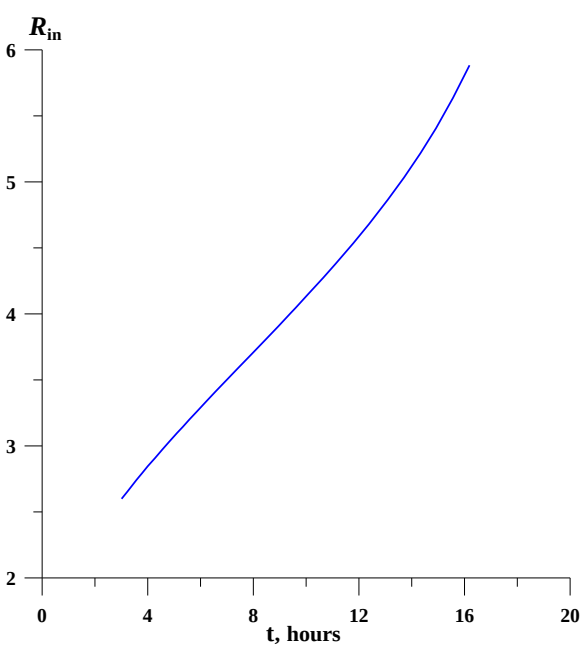

Fig. 3. The dimensionless radius of thermal influence versus time, wells Ro77, r_w=0.108 m, a = 0.0041 $m^2 \cdot hr^{-1}$.

CONCLUSION

A new semi-analytical equation for estimation of the radius of thermal influence at cement hydration is proposed.

REFERENCES

Dillenbeck, R.L., Heinold, T., Rogers, M.J., Mombourquette, I.G. (2002), "The Effect of Cement heat Hydration on the Maximum Annular Temperature of Oil and Gas Wells". *SPE 77756 presented at the SPE Annual Technical Conf.* 29 September – 2 October 2002, San Antonio, Texas.

Kutasov, I.M. (1999), "*Applied Geothermics for Petroleum Engineers*". Elsevier.

Kutasov I. M. (2007), "Dimensionless temperatures at the wall of an infinitely long, variable-rate, cylindrical heat source". *Geothermics*, **36**, 223-229.

Romero, J., Loizzo, M. (2000), "The Importance of Hydration Heat on Cement Strength Development for Deep Water Wells", *SPE paper 62894 presented at the 2000 SPE Annual Technical Conference and Exhibition*, Dallas, Texas, 1-4 October.