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Using Drilling and Completions Temperature Measurements to Estimate Formation Temperatures in a Research Test Well

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ABSTRACT

This paper strives to estimate temperature profiles of annulus fluid and casing along the wellbore after the well shut-in during drilling and completions operations using published models and measured temperature points. With known annulus fluid temperature at the end of circulations, circulation duration, formation thermal diffusivity and wellbore dimension, either a pseudo temperature log or the undisturbed static formation temperature (SFT, in this paper SFT always means undisturbed SFT) can be calculated if one of them is known. Bullard's method (1947) and Kutasov's method (1987) are selected to calculate the wellbore temperature during the shut-in period. We demonstrated that both approaches could match the temperature measurements very well in our presented cases.

The SFT and multiple temperature logs were obtained during open-hole drilling and completions operations in a research test well located in Grimes County, Texas. We obtained various temperature logs during drilling and completions operations through the conventional and wired-telemetry MWD (measurement-while-drilling) tools, live-streaming EMS (enhanced measurement sub) and ASM (along-string measurement) tools in the open-hole and fiber-optic measurements in the cased-hole. In this paper, the SFT was first assumed unknown and the temperature logs were used to calculate the SFT profile along the wellbore. The results were encouraging as they matched the downhole measurements. Similarly, a pseudo-temperature log can be computed using the same set of equations once the field SFT profile is known.

In the open-hole examples, the fluid circulation time was practically adjusted to reflect the "true" circulation time which is defined as the moment when the drill bit contacted the in-situ formation at a specific depth during drilling this interval. This would honor the initial SFT condition at the beginning of the fluid circulation and make both the Bullard and Kutasov methods valid. Therefore, only at the total depth of the well, the "true" circulation time for the heat emission from the wellbore is the actual circulation bottom-up (CBU) time, but at other depths, it varies and is much greater than the CBU time. In the cased-hole applications, the published analytical solutions can be applied directly for all depths. The initial conditions are honored when the circulation begins after an extended shut-in time elapses before the circulation commencement. The case studies demonstrated in the test well illustrate that the SFT profile or a pseudo-temperature log can be predicted fairly accurately with the published analytical solutions when the correct initial temperature conditions apply.

1. INTRODUCTION

Undisturbed, static formation temperature (SFT) is a critical input for the design and execution of geothermal drilling, completions and production operations. The wellbore temperature profile is also essential for drilling and completions fluid selection, cementing design and operations, and drilling equipment design and selection. Direct measurement of downhole temperature using a dedicated observation well with a permanent temperature sensing device can be a reliable approach but is time-consuming and cost prohibitive. Massive real-time temperature data can be obtained from drilling and completions operations in any oil, gas, geothermal or CCUS (carbon capture utilization and storage) wells using conventional MWD (measurement while drilling), LWD (log while drilling), or other modern wired MWD tools as part of the typical drilling BHA (bottom hole assembly). But the measured data are affected by transient flow dynamics and the Joule-Thomason effect resulting from the pressure change, which renders the measured temperature significantly deviating from SFT required for the above operations. Wellbore shut-in temperature is not typically acquired during normal drilling operations. However, for an exploration well or a delineation well in a new field, a planned wiper trip to the last casing shoe can be used as a "pseudo" shut-in and the MWD tools can still record memory temperature data during this operation. With the knowledge of this shut-in temperature and the annulus fluid temperature at the end of the circulation period, the geothermal profile (i.e., the undisturbed SFT) can be modeled using the selected models discussed in this paper.

Data frequency or sampling rate varies significantly among these tools from one single temperature data at each connection while a conventional MWD tool pulsing to a high-speed, high frequency wired MWD up to 57.6 Kbps bidirectional data rate through a wired drill pipe system (Pink et al., 2017). Surface mud inlet and outlet temperature are often measured and recorded but it is difficult to interpret bottomhole SFT from them. In addition, wireline line logging tools are often equipped with temperature sensors to get bottomhole temperature at a specific shut-in time after the last fluid disturbance (i.e., circulation). These data can be wisely used to interpret undisturbed SFTs.

Bullard (1947) used a line-source approach to calculate the radial temperature profile surrounding the wellbore during fluid circulation and to determine the wellbore wall temperature development over time after the well is shut in by using a superposition approach. One of its key assumptions is neglecting the wellbore size impact on the temperature. This assumption is valid when circulation time is long, but is questionable if one is interested in a short circulation time. Kutasov (1987) and Kutasov et al., (1988) presented a similar analytical wellbore shut-in temperature model to Bullard (1947) but with an adjusted circulation time to improve the estimation accuracy on wellbore temperature during shut-in (Wu et al., 2015; Chen et al., 2022) when the circulation time is short. In both methods, the circulating temperature is treated as a constant value, which is a reasonable assumption, especially when circulating bottom up after the well reaches total depth (Kutasov, 1987; Chen et al., 2022). Multiple open-hole and cased-hole examples in this paper demonstrated that using the circulation temperature at the end of the circulation period is acceptable for both the open-hole and cased-hole applications. Kabir et al. (1996) presented an analytical approach to determining the circulating fluid temperature during drilling operations if the circulation temperature is unavailable.

In petroleum engineering, the Horner method for pressure transient analysis after well shut-in is widely used to generate identical wellbore shut-in temperature solutions as Bullard's method (Horner, 1951; Kutasov and Eppelbaum, 2005). There are some other "simplified" solutions (Carslaw and Jaeger, 1959, p.260; Middleton, 1979; Barelli and Palama, 1981; Leblanc et al., 1981; Ascencio et al., 1994, 1997; Espinosa-Paredes and Garcia-Gutierrez, 2003) to calculate the shut-in wellbore temperature by using the dimensionless shut-in time only (no need for the input of the dimensionless circulation time) but may compromise the accuracy of matching the measured temperature values (Chen et al, 2022).

Eppelbaum and Kutasov (2011) pointed out two values of shut-in temperature (for a given depth) are needed to estimate the undisturbed formation temperature (SFT) and effective bore-face temperature during the drilling period (T_{w0}), using Eq. (4). By comparing the measured and modeled shut-in temperature (Chen et al., 2022), we learned that the wellbore temperature at the end of the circulation period can be treated as the "effective" bore-face temperature, T_{w0}, which can typically be obtained through the MWD tools in today's drilling operations. Therefore, we can solfe SFT if T_{w0} and shut-in temperature at a specific shut-in time after a specific circulation duration are known. Likewise, if knowing T_{w0} and SFT, a shut-in temperature at a specified shut-in time after a specified circulation time can be solved using the same set of dimensionless solutions.

The wellbore schematic for the innovation research test well is shown here (Hewlett et al., 2021; Chen et al., 2022).

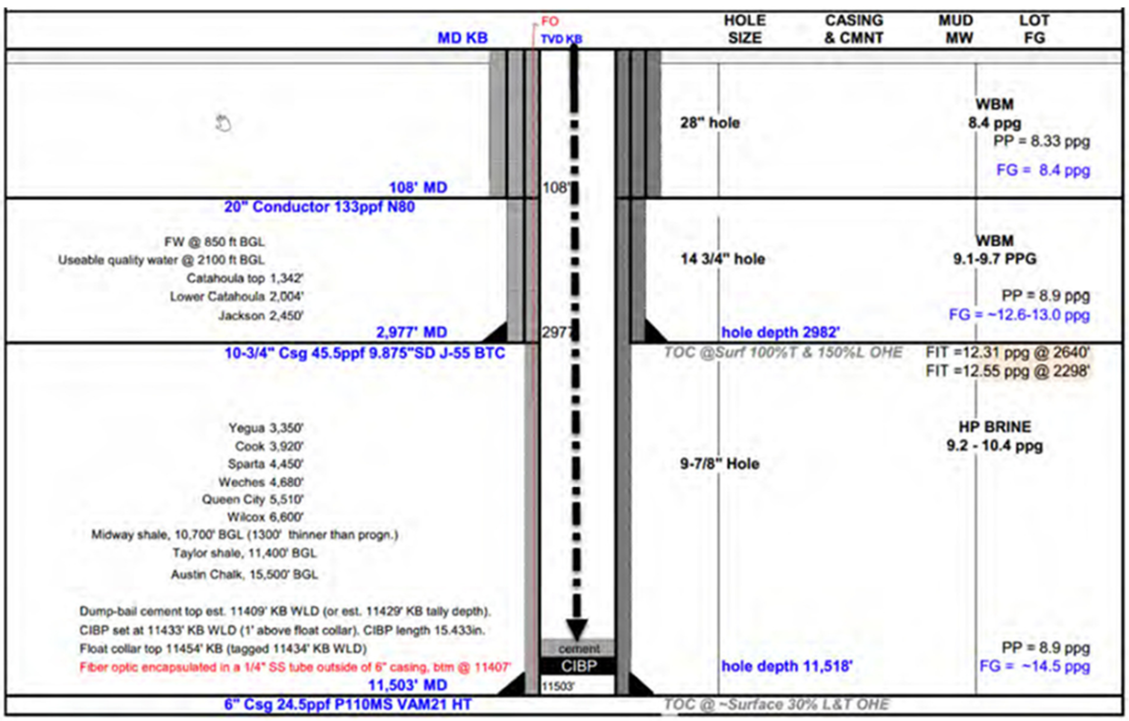

Figure 1: Test well schematic.

2. KEY ASSUMPTIONS ADOPTED IN THIS STUDY

Heat transfer in subsurface formation is a transient heat conduction process if there is no fluid flow in the formation. This is consistent with Ramey (1962), Schoeppel (1966) and Shen and Beck (1986). In practice, we often neglect the impact of natural convection in the cased hole and open hole as well as the thermal diffusion in the open hole case.

Thermal diffusion is negligible as Midway and Navarro shales have very low permeability compared with the meaningful value that can contribute to the production temperature profile due to natural convection and thermal diffusion. Beckers et al. (2022, Fig. 17) showed that the natural convection was negligible heat conduction played a dominant role in thermal energy harvest from a geothermal well completed in a reservoir with a reservoir permeability of 10^{-18} m^2 (or ~1,000 nano-darcy). Midway shale and Navarro shale have an average porosity of 5% and permeability of 3.55 and 14.1 nano-darcy, respectively (Pitman and Rowan, 2012, p7). The Wilcox sand may have much higher permeability than the shale formations; however, the predicted SFT or shut-in temperature profiles in the open-hole examples in this paper do not indicate the higher Wilcox sand permeabilities have any significant impact on the heat transfer in an open-hole environment.

For the cased hole case, we assumed the temperature at the casing inside (T_{ci}) is equal to the temperature at the outside of the casing (T_{co}) since the steel tubular usually has a very high heat conductivity, and we further assumed they are equal to the fluid temperature in the annulus (T_a). This assumption enables us to use the T_{co} from the fiber-optic distributed temperature sensing (DTS) cable as the annulus fluid temperature T_a. For the shut-in temperature study, the amount of heat stored in the relatively small-sized borehole dimensions (e.g., 9-7/8" hole size and 6" casing outer diameter) is negligible compared with the infinity geothermal "reservoir". Therefore, only a thermal diffusivity of formation is needed if we assume that the wellbore region has the same thermal diffusivity as the formation. This assumption has been used widely in literature for simplification purposes (Jaeger, 1956; Kutasov, 1987).

We also assumed that the thermal properties of formation are constants. The study uses a single value of the formation thermal diffusivity for the entire wellbore length, which generated consistent modeling results compared with the actual temperature measurements. The formation thermal diffusivity from the published literature for the Midway and Navarro shales (Pitman and Rowan, 2012) was calibrated against the measurements after modeling the temperature recovery process for a fixed depth (Chen et al., 2022). Based on the same work (Pitman and Rowan, 2012), the calculated Wilcox sand thermal diffusivity (~0.035 ft^2/hr) is very close to what is being used for Midway and Navarro shales in this study (0.03 ft^2/hr). The Wilcox sand composes a majority of the production hole section.

3. PUBLISHED WELLBORE SHUT-IN TEMPERATURE SOLUTIONS ADOPTED IN THIS STUDY

Bullard (1947) developed a wellbore temperature solution with the input of wellbore dimensions, formation thermal diffusivity, fluid circulation time, fluid temperature at the end of circulation, far-field undisturbed temperature, and wellbore shut-in time. The wellbore dimensionless shut-in temperature solution T_{sD} at the wellbore wall can be expressed in Eq. (1) in terms of dimensionless mud circulation time t_{Dc} and dimensionless shut-in time t_{Ds} (Kutasov 1999, p.159; Kutasov and Eppelaum, 2005; Chen et al., 2022).

$$T_{sD}(r_D = 1, t_{Dc}, t_{Ds}) = \frac{-Ei\left(-\frac{1}{4t_{Ds}}\right)+Ei\left(-\frac{1}{4(t_{Dc}+t_{Ds})}\right)}{Ei\left(-\frac{1}{4t_{Dc}}\right)} \tag{1}$$

$$t_{Dc} = \frac{\alpha_e t_c}{r_w^2},\ t_{Ds} = \frac{\alpha_e t_s}{r_w^2}, r_D = \frac{r}{r_w}, T_{sD} = \frac{T_s(r_w,t_s)-T_\infty}{T_{w0}(r_w,t_c)-T_\infty} \tag{2}$$

Where *Ei* is the exponential integral function. For a non-zero x (Carslaw and Jaeger 1959, p.262),

$$\mathrm{Ei}(-\mathrm{x}) = -\int_{\mathrm{x}}^{\infty}\frac{e^{-\mathrm{u}}}{\mathrm{u}}d\mathrm{u} \text{ or } \mathrm{Ei}(\mathrm{x}) = -\int_{-\mathrm{x}}^{\infty}\frac{e^{-\mathrm{u}}}{\mathrm{u}}d\mathrm{u} \tag{3}$$

For convenient programming in Microsoft Office Excel, the Ei function approximation (Swamee and Ojha, 1990; Giao, 2003) is utilized with acceptable accuracy.

The dimensionless time and dimensionless distance are given in Eq. (2) where

r = wellbore radial distance, ft

r_D = dimensionless wellbore radial distance

r_w = wellbore radius, ft

t_c = circulation time, hour

t_s = shut-in time, hour

T_s = shut-in temperature at the wall, °F

T_{w0} = wellbore wall temperature at the end of the fluid circulation (at $t = t_c$ or $t_s = 0$), °F

T_∞ = far-field formation temperature, °F. In this paper's applications, T_∞ is considered equal to the undisturbed SFT.

α_e = formation (earth) thermal diffusivity, ft^2/h

Kutasov (1987) and Kutasov et al., (1988) adjusted the dimensionless circulation time definition (Bullard, 1947) by using the ratio of the dimensionless accumulative heat flow to the dimensionless heat flow rate data obtained from several previously published pioneering literatures.

$$T_{sD}(r_D = 1, t_{Dc}, t_{Ds}) = \frac{Ei\left(-\frac{1}{4t_{Dc}^*}\right)-Ei\left[-\left(\frac{1}{4t_{Dc}^*}+\frac{1}{4t_{Ds}}\right)\right]}{Ei\left(-\frac{1}{4t_{Dc}^*}\right)} \tag{4}$$

$$t_{Dc}^* = \begin{cases} t_{Dc}\left[1+\frac{1}{1+\frac{7}{8}[ln(1+t_{Dc})]^{2/3}}\right];\ t_{Dc} \le 10 \\ \frac{t_{Dc}[lnt_{Dc}-exp(-0.236\sqrt{t_{Dc}})]}{lnt_{Dc}-1};\ t_{Dc} > 10 \end{cases} \tag{5}$$

Based on Eq. (2), dimensional T_s and dimensional SFT can be calculated if the remaining parameters are known or solved earlier:

$$T_s(r_w, t_s) = T_\infty + T_{sD}[T_{w0}(r_w, t_c) - T_\infty] \quad (6)$$

$$SFT\ (or\ T_\infty) = \frac{T_s(r_w,t_s) - T_{sD}T_{w0}(r_w,t_c)}{1 - T_{sD}} \quad (7)$$

4. PROCEDURE OF CALCULATING SFT OR SHUT-IN TEMPERATURE FROM WELLBORE FLUID TEMPERATURE MEASUREMENTS DURING DRILLING AND COMPLETIONS

The drilling operations are typically equipped with MWD tools to give good measurements of the drilling circulating fluid temperature. The MWD temperatures are used to interpolate the wellbore temperature profile along the wellbore length at the end of the fluid circulation (T_{w0}) which is also called an effective drilling fluid temperature (Eppelbaum and Kutasov, 2011).

Calculation procedure:

1. Determine the circulation time in hours (t_c), dimensionless circulation time (t_{Dc}) and modified dimensionless circulation time (t_{Dc}*)
2. Using the given shut-in time in hours (t_s) to calculate the dimensionless shut-in time (t_{Ds}).
3. Calculate the dimensionless wellbore shut-in temperature (T_{sD}) using Eq. (1) (Bullard's method) or Eq. (4) (Kutasov's method).
4. Using the known wellbore temperature at the end of the circulation period (T_{w0}) to calculate SFT using Eq. (7).
5. Similarly, the wellbore shut-in temperature (T_s) can be calculated using Eq. (6) if SFT is known.

4.1 Open Hole Drilling Case

An open-hole temperature log was acquired after 32-hour fluid stagnant time while a wiper trip to the casing shoe was being conducted (Hewlett et al, 2021; Chen et al., 2022). However, during operations, intermittent and irregular minor disturbances occur such as filling in the open hole during tripping out of the hole to keep the hole full. Since the rig only pumped the "required" volume to make the hole full instead of a "circulation", the resulting disturbance to the wellbore temperature profile is minimal. During this temperature recovery period, there were 10 ASM (along string measurements) and 1 EMS (enhanced measurement system) tools in the bottom hole assembly and along the drilling string. These tools recorded and live-streamed downhole temperature measurements during the wiper trip thorough a wired telemetry. The specific well depths are selected to match the ASM / EMS tool sensor depths prior to and during circulation bottom-up (CBU), which are computed by subtracting the tool depth offset captured in Rigsense from the bit depth.

The circulation time at different depths used in the calculations was adjusted so that the "initial" temperature at different depths at the start of the circulation remains at the undisturbed static formation temperature. The circulation time used for modeling is the actual CBU (circulating bottom up) time only at the bottom of the open hole. If using the same circulation duration such as the CBU time of 6 hours for all the depths, results of modeled SFT or shut-in temperature would be misleading. For depths above the surface casing shoe, as the circulation time is sufficiently long, it will not make any noticeable difference if calculating the circulation time from the start of the surface hole drilling or from the start of the production hole drilling. The temperature in the wellbore region typically resumes to the SFT profile after an adequate fluid stagnant time between the two operations.

In Figure 2, T_a is the annulus fluid temperature measured by the EMS and ASM tools. During the temperature recovery, the temperature profile deviates from T_{w0} (the dashed blue line with circles) toward the T_s line (yellow line with solid circles) and the SFT line (black line), i.e., the top part (above ~5000 ft depth) of the wellbore gets cooler while the lower part of the wellbore (below ~5000 ft depth) becomes warmer. The intersection of these two curves is the cross-over point (Schumacher and Moeck, 2020).

It can be observed that the calculated SFT using Bullard's method (blue diamonds) or Kutasov's method (red squares) match the measured SFT very well. The exception is at the very bottom of the hole where the dimensionless circulation time is the smallest (t_{Dc} = 0.72) compared with other depths of the open hole. This small value of the dimensionless circulation time (i.e., $t_{Dc} < 1$) may push the limit of the accuracy of Eq. (1) and Eq. (4) (Kutasov, 1989).

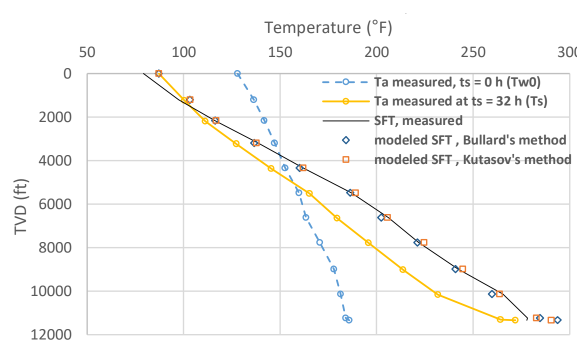

Figure 2: Modeled SFT using 32-hour shut-in temperature measurements in an open hole.

4.2 Cased Hole Flowing with 2-7/8" P110 Tubing

A distributed temperature sensing (DTS) fiber-optic is permanently installed on the outside diameter of the production casing. All the downhole temperature measurements in the cased hole examples are continuously recorded through the fiber-optic cable along the full length of the wellbore. The temperature is recorded every five minutes for every foot of hole depth.

After the production casing was set, a string of 2-7/8" P110 tubing was run to about 11,200 ft TVD (true vertical depth). Before fluid circulation started, the wellbore had been static for several months. Therefore, the initial condition of the wellbore temperature before the circulation is in equilibrium with the geothermal temperature. In Figure 3, Kutasov's method was used to calculate the SFT profile. SFT predictions based on the 2-hour and 12-hour shut-in temperatures are consistent with the measured SFT profile. This example illustrates that a temperature log can be conducted 2 hours after the circulation stops and generate an acceptable far-field geothermal temperature profile.

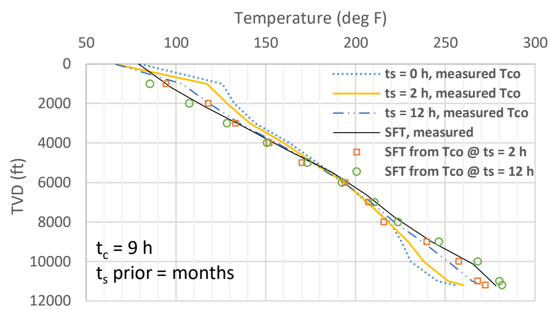

Figure 3: Modeled SFT using 2- and 12-hour shut-in temperature measurements for a 2-7/8" P110 tubing completion.

4.3 Cased Hole Reverse Flowing with 2-7/8" L80 Tubing

A 2.13-hour reverse circulation was conducted when the 2-7/8" outer-diameter string bottom was located at 6887 ft depth. Before the circulation started, the well had been shut-in for 65 hours. The well was shut in for about 12 hours after the reverse circulation stopped. Figure 4 plotted the calculated SFT based on the shut-in temperature at 10 hours of shut-in and compared it with the measured SFT profile.

The discrepancy between calculated and measured SFT is less than 2 ℉ at 2000-3000 ft but up to 8 ℉ at 6000 ft depth. This magnitude of difference may be caused by the approximation of the initial condition at $t_c = 0$ which is about 2-8 ℉ difference (lower) than the undisturbed SFT. Another reason for the discrepancy could be the dimensionless flowing time $t_{Dc} = 0.69$, which may challenge the validity and accuracy of Eq. (1) and Eq. (4) for small times ($t_{Dc} < 1$) (Kutasov, 1989).

For this example, the SFT calculated temperature from Kutasov's method and Bullard's method almost same. Moreover, in this example the calculated dimensionless shut-in temperature has the same value of four digits after the decimal point when using the Ei solver (Petroleum Office) to get a more "exact" solution compared with using the empirical Ei correlations (Swamee and Ojha, 1990).

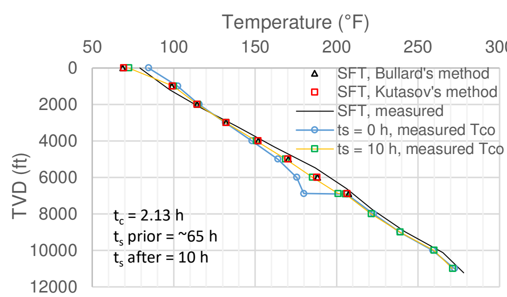

Figure 4: Modeled SFT using 10-hour shut-in temperature measurements after 2.13-hour reverse circulation at 6887 ft for a 2-7/8" L80 tubing completion.

5. ESTIMATING THE SHUT-IN WELLBORE TEMPERATURE WITH KNOWN SFT PROFILE

Once the undisturbed static formation temperature (SFT) is known, the wellbore shut-in temperatures can be calculated as a function of the preceding circulation time and subsequent shut-in time. The calculation procedure was shown previously in section 4.

5.1 Open Hole Drilling Case

The same input data of the circulation duration and the temperature value at the end of the circulation in section 4.1 are used in this section. Along the wellbore length (above ~10,000 ft) the modeled shut-in temperature using either Bullard's method or Kutasov's method appears to be very consistent with the actual downhole measurements. At the very bottom of the hole, the predicted shut-in temperature is up to ~6°F lower than the measured value. A small dimensionless circulation time at the deepest temperature sensor depth, $t_{Dc} = 0.72 < 1$ could primarily contribute the modeling discrepancy.

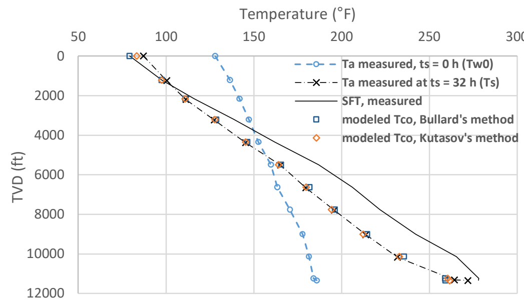

Figure 5: Calculated wellbore shut-in temperature after 32-hour shut-in using known SFT for an open hole case.

5.2 Cased Hole with a P-110 Tubing Completion

Figure 6 shows that as the wellbore shuts in, the wellbore is gradually warmed up to the original undisturbed SFT profile. Above the cross-over point near 5000 ft depth, the formation cools down and the temperature profile moves towards the SFT line while below the cross-over point the wellbore warms back and the temperature profile moves towards the original SFT profile. The shut-in temperature curve approaches closer to the SFT profile as the shut-in time becomes longer. For this example, after 12-hour shut-in, the maximum temperature separation from the SFT line is no more than 11°F at ~10,000 ft depth.

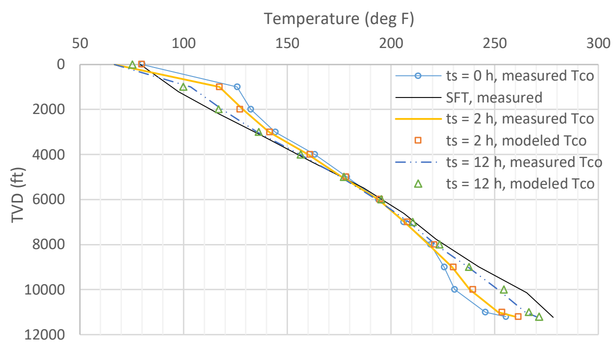

Figure 6: Calculated wellbore shut-in temperature after 2- and 12-hour shut-in using known SFT in a cased hole in a P-110 tubing completion.

5.3 Cased Hole Reverse Circulation Case

An L-80 2-7/8" work string was run to 6887 ft and a reverse circulation (i.e., down annulus and up tubing) was conducted at ~130 gal/min for about 2.13 hours. Then the circulation ceased and the wellbore fluid stayed stagnant for ~12 hours. The temperature at the outside diameter (OD), T_{co}, of the 6" casing was continuously measured with a permanently installed fiber-optic cable. The consistency between the modeled and measured casing OD temperature can be found in Figure 7 for both Kutasov's method and Bullard's method.

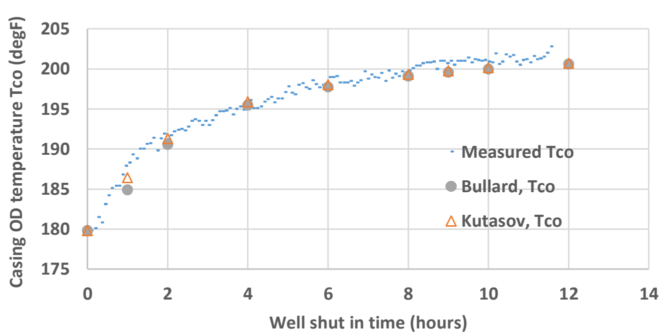

Figure 7: Calculated wellbore shut-in temperature at 6887 ft depth (below ground level) up to 12-hour shut-in after a reverse circulation with t_c = 2.13 hours at 130 gal/min.

Using Kutasov's method, we calculated the wellbore shut-in temperature profile along the full wellbore as shown in Figure 8. It reveals that the initial temperature at the start of circulations (t_c = 0 hr) almost falls on top of the original SFT. The calculated shut-in temperature profile after 10 hours of recovery (t_s = 10 hr) is consistent with the measured values. To recover the 2.13-hour heat disturbance due to fluid circulation, 10 hours of heat recovery is nearly sufficient to reach the initial SFT condition. The reverse circulation is made at approximately 6887 ft as determined by the fiber-optic DTS (distributed temperature sensing) temperature measurements (Chen et al., 2022) so the temperature profile below this depth remains undisturbed at the initial condition (i.e., t_c = 0) and is not impacted by any fluid movement in the tubing or in the annulus as shown in Figure 8.

The maximum discrepancy between the predicted and measured T_{co} is about 7 ℉ at 6000 ft depth. The same explanation can be seen in section 4.3.

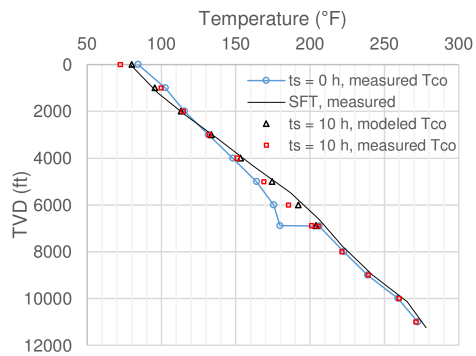

Figure 8: Calculated wellbore shut-in temperature profile after 10-hour shut-in after a reverse circulation at 6887 ft with t_c = 2.13 hours, 130 gal/min.

6. CONCLUSIONS

In general, Bullard's method (1947) and Kutasov's method (1987) predicted consistent wellbore shut-in temperature and static formation temperature (SFT) and the predictions are consistent with the measurements in the open hole and the cased hole applications. However, Bullard's method might be less accurate for the small shut-in and circulation time (e.g., when t_s/t_c=0.1 and t_{Ds} = 0.1), as demonstrated in Chen et al. (2022). Depending on the known variables, either the SFT or the shut-in temperature at a specific shut-in time can be predicted using either of these two published analytical models.

In open-hole oil and gas or geothermal drilling applications, conventional MWD tools can pulse and record the bottom hole temperature measurements. The shut-in temperature or a pseudo-temperature log can be calculated using the published analytical solutions with the known regional or field geothermal temperature profile. Likewise, the SFT profile can be calculated or calibrated if a temperature log is available after the drilling operation stops.

The selection of the starting time of the circulation period becomes critical in open-hole applications. The modeling results showed that one has to choose the starting time for t_c = 0, which can approximate the initial SFT condition. In most cases (e.g., when drilling a long production hole), the moment of the drill bit contacting the formation should be chosen as the start of the circulation period for this specific depth. For the upper hole sections already cased off, the shut-in period prior to the circulation commencement in the current hole section, e.g., drilling operations in the upper hole sections ceased due to tripping and running surface casing, does not seem to be very important. Typically, the effective "shut-in" time (e.g., tripping and running surface casing) is long enough at shallow depths so the near-wellbore formation temperature profile at the start of the production hole drilling can be treated as the original SFT condition, for the surface hole section.

It is also demonstrated that a single value of the formation thermal diffusivity seems sufficient when modeling the shut-in temperature profile for the entire wellbore depth.

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REFERENCES

Ascencio, F.L., García, A., Rivera, J.R., and Arellano, V.M.: Estimation of undisturbed formation temperatures under spherical-radial heat flow conditions. *Geothermics*, (1994) **23**, 317-326.

Ascencio, F., Rivera, J., and Samaniego, F.: On the practical aspects of determination of true reservoir temperatures under spherical heat flow conditions, Proceedings, *21st Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford, CA (1997).

Barelli, A., and Palamà, A.: A new method for evaluating formation equilibrium temperature in holes during drilling. *Geothermics*, (1981) **10**, 95-102.

Beck, A.E., and Shen, P.Y.: Temperature distribution in flowing liquid wells. *Geophysics*. VOL. **50**. NO.**7** (JULY 1985); P. 1113-1118. https://doi.org/10.1190/1.1441984.

Beckers, K.F., Rangel-Jurado, N., Chandrasekar, H., Hawkins, A.J., Fulton, P.M., and Tester, J.W.: Techno-Economic Performance of Closed-Loop Geothermal Systems for Heat Production and Electricity Generation, *Geothermics* Volume **100**, (2022), 102318, ISSN 0375-6505, https://doi.org/10.1016/j.geothermics.2021.102318.

Bullard, E.C.: The Time Necessary for a Bore Hole to Attain Temperature Equilibrium. *Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society*, Volume **5**, Issue 5, (May 1947), Pages 127–130, https://doi.org/10.1111/j.1365-246X.1947.tb00348.x

Carslaw, H.S., and Jaeger, J.C.: *Conduction of Heat in Solids*, 2nd Ed., Oxford Univ. Press, London, (1959).

Chen, G., Wright, C., and Goswami, J.C.: Wellbore Shut-In Temperature Study After Fluid Circulations in a Fit-For-Purpose Research Well in Grimes County, Texas. Paper presented at the *56th U.S. Rock Mechanics/Geomechanics Symposium*, Santa Fe, New Mexico, USA (June 2022). doi: https://doi.org/10.56952/ARMA-2022-0099

Chen, G., Wright, C., Guidry, K., Bordelon, B., and Daigle R.: Using fiber-optic downhole temperature measurement to aid fishing operations in a research well in Grimes County, Texas. Presented in the *SPE Workshop: Fiber-Optic Sensing Applications for Well, Reservoir, and Asset Management*, (August 2022), San Antonio, Texas.

Eppelbaum, L.V., and Kutasov, I.M.: Determination of the formation temperature from shut-in logs: Estimation of the radius of thermal influence, *Journal of Applied Geophysics*, Volume **73**, Issue **3**, (2011) Pages 278-282, ISSN 0926-9851, https://doi.org/10.1016/j.jappgeo.2011.01.011.

Espinosa-Paredes G., and Garcia-Gutierrez A.: Estimation of static formation temperatures in geothermal wells. *Energy Conversion and Management*, (2003) **44** 1343–1355.

Giao, P. H.: Revisit of well function approximation and an easy graphical curve matching technique for Theis' solution. *Ground Water*. 41 (**3**) (2003): 387–390. Doi:10.1111/j.1745-6584.2003.tb02608.x. ISSN 1745-6584.

Hewlett, R., Pink, S., Goswami, J., Debrosse, D., and Wright, C.: Interval density analysis from a distributed absolute pressure array. Paper presented at the *SPE Annual Technical Conference and Exhibition*, Dubai, UAE, (2021). Paper Number: SPE-206021-MS. https://doi.org/10.2118/206021-MS.

Horner, D.R.: Pressure Build-Up in Wells. *Proceedings of the 3rd World Petroleum Congress*, (1951), 25-43.

Jaeger, J.C.: Numerical Values for the Temperature in Radial Heat Flow, *Jour. of Math. Phys*., **34** (1956), 316-321.

Kabir, C. S., Hasan, A. R., Kouba, G. E., and Ameen, M.M.: Determining Circulating Fluid Temperature in Drilling, Workover, and Well Control Operations. *SPE Drill & Compl* **11** (1996): 74–79. doi: https://doi.org/10.2118/24581-PA

Kutasov, I.M.: Dimensionless Temperature, Cumulative Heat Flow and Heat Flow Rate for a Well With a Constant Bore-face Temperature, *Geothermics*, **16**, No. 2, (1987), 467-472.

Kutasov, I.M., Caruthers, R.M., Targhi A.K., and Chaaban, H.M.: Prediction of Downhole Circulating and Shut-in Temperatures. *Geothermics*, **17**, (1988), 607-618.

Kutasov, I. M.: Application of the Horner method for a well produced at a constant bottomhole pressure. *SPE Form Eval* 4 (**01**) (1989): 90–92. Paper Number: SPE-15143-PA.

Kutasov, I.M., and Eppelbaum, L.V.: An Improved Horner Method for Determination of Formation Temperature. *Proceedings World Geothermal Congress*, Antalya, Turkey (2005).

Leblanc, Y., Pascoe, L. J., and Jones. F. W.: The temperature stabilization of a borehole. *Geophysics*, v. **46**, (1981), p. 1301-1303.

Lee, T.-C.: Estimation of formation temperature and thermal property from dissipation of heat generated by drilling. *Geophysics*, VOL. 47, NO **II** (1982): P. 1577-1584.

Middleton, M. F.: A model for bottom-hole temperature stabilization, *Geophysics* **44**, (1979), 1458-1462.

Petroleum Office, Ei() function online solver. https://petroleumoffice.com/function/expintegralei. Last accessed January 3, 2023.

Pink, T., Cuku, D., Pink, S., Chittoor, V., Goins, A., Facker, B., and Hanford, R.: World First Closed Loop Downhole Automation Combined with Process Automation System Provides Integrated Drilling Automation in the Permian Basin. Paper presented at the *SPE/IADC Drilling Conference and Exhibition*, The Hague, The Netherlands, (March 2017). doi: https://doi.org/10.2118/184694-MS

Pitman, J.K., and Rowan, E.: Temperature and Petroleum Generation History of the Wilcox Formation, Louisiana. USGS Open-File Report 2012–1046, (2012). Pp.55.

Ramey, H. J. Jr.: Wellbore heat transmission. *J. Petrol. Technol*., **14** (1962), pp. 427-435. SPE-96.

Schumacher, S., and Moeck, I.: A new method for correcting temperature log profiles in low-enthalpy plays. *Geotherm Energy* **8**, 27 (2020). https://doi.org/10.1186/s40517-020-00181-w.

Schoeppel R.J., and Gilarranz, S.: Use of Well Log Temperatures to Evaluate Regional Geothermal Gradients. *J Pet Technol* **18** (06): 667–673 (1966) SPE-1297-PA. https://doi.org/10.2118/1297-PA

Swamee, P.K., and Ojha, P.S.C.: Pump test analysis of confined aquifer, *Journal of Irrigation and Drainage Engineering*, Vol. 116, No. **1** (1990): 99-106.

Wu, X., Xu, B., and Ling, K.: A Semi-analytical Solution to the Transient Temperature Behavior along the Vertical Wellbore after Well Shut-in. *Journal of Petroleum Science and Engineering*, **131** (2015), 122-130.