ESTIMATION OF STATIC RESERVOIR TEMPERATURE DURING DRILLING OPERATIONS

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A reliable static formation temperature is valuable in determining casing depths, establishing geothermal gradients, analyzing logs and estimating fluid potential for geothermal reservoirs. The conventional drilling mud fluid systems associated with geothermal well drilling distort the static formation temperature near the wellbore because the circulating mud temperature is normally much less than the static formation temperature. As a result, a wellbore temperature recorded during drilling operations does not reflect the static formation condition.

The use of a Horner-type temperature buildup plot, similar to the conventional pressure buildup method, has been suggested (1) for estimating static formation temperature. The method has proven satisfactory in a number of oil and gas field cases. Recently, Dowdle and Cobb (2) investigated the conditions under which the Horner temperature plot can be used to yield representative static formation temperatures. They concluded that the method is reliable if both the wellbore temperature gradient changes very slowly and the mud circulation time is short. However, in geothermal operations, temperature gradients are usually more extreme and longer circulation times are required to cool the wellbore sufficiently for logging. Therefore, the method has proved to be less reliable.

As an alternate solution, dimensionless Horner temperature type curves have been developed for determining reliable static formation temperatures under normal geothermal drilling conditions in the Imperial Valley, California.

Basic Temperature Equation

The temperature distribution near the wellbore at any time is described in the following differential equation (3):

$$\frac{\partial T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{C_p\rho}{K}\frac{\partial T}{\partial t} \qquad (1)$$

Subject to the assumptions of conductive heat flow in the horizontal, cylindrically symmetrical, homogeneous medium surrounding the wellbore, the solution to the above equation is dependent on a set of boundary conditions. Unlike the "diffusivity" equation used in describing pressure behavior, the inner boundary condition is not constant because the wellbore temperature gradient is changing during circulation.

Edwardson *et al.* (4) numerically solved the above equation at various distances from the wellbore for a $K/C_p\rho r^2$ parameter value of 0.4. This number is derived from the following estimates from limestone, sandstone and shale hydrocarbon reservoir properties: K = 1.303

Btu/hr-ft-°F; C_p = 0.21 Btu/lb-°F; and ρ = 144 lbs/cu ft. The wellbore diameter was assumed to be 7.875 inches. The numerical solution in the form of a dimensionless Horner temperature type curve is shown in Fig. 1 for $r_D = 1$. Dowdle and Cobb[2] demonstrated that the nonlinearity of these Horner temperature curves is due to the slow change in wellbore temperature gradient during the mud circulation period.

Although the dimensionless curves in Fig. 1 are based on the $K/C_p\rho r_w^2$ value of 0.4, their adaption to reservoirs with different thermal properties has been demonstrated [2] [4]. The values of circulation time (t_k) in Figure 1 can simply be replaced with values corresponding to another set of conditions. For a case of $K/C_p\rho r_w^2$ equal to 0.8, the curve for t_k = 2.4 hours in Fig. 1 would be redesignated t'_k = 1.2 hours. Empirical data determined during drilling operations can be plotted on Fig. 1 and a representative $K/C_p\rho r_w^2$ value for the system can be determined.

Figure 2 shows actual data points collected during Imperial Valley drilling operations plotted on the theoretical Horner buildup curves for $K/C_p\rho r_w^2$ equal to 0.4. Clearly, a circulation time in excess of 14 hours would be required to define the $K/C_p\rho r_w^2$ value or to use the curves shown in Fig. 1.

Circulation times on this order are excessive and costly. For these theoretical type curves to be useful in Imperial Valley geothermal reservoirs, t_k values down to 0.05± would need to be generated.

Development of Empirical Type Curves

Rather than expanding the numerical solutions presented by Edwardson et al., sufficient temperature data has been collected from the drilling operations in more than one geothermal area of the Imperial Valley to construct an empirical set of Horner temperature buildup curves. Various scheduled operations during drilling provided opportunities to measure directly wellbore temperatures at various depths and times after mud circulation was stopped. For instance, multiple maximum recording thermometers were run during logging operations and also during hole deviation surveys. In addition, Amerada-type temperature recorders were run at various depths and circulation histories.

Wellbore temperature change with time after circulation stopped was recorded in several wells at various formation depths for a wide range of circulation times. Following completion, a history of temperature gradient surveys defined the static formation temperature at any particular depth. Having measured the static formation temperature and recording the wellbore temperature changes with time after various circulation periods, the curves in Fig. 3 were constructed.

Accuracy of the Static Formation Temperature Estimation

The empirical set of curves in Fig. 3 was developed from data obtained over a formation depth interval in excess of 4500 feet in one area of the Imperial Valley. The uniform spacing of the curves suggests that there was no appreciable change in the reservoir thermal properties with depth or temperature variation. The curves in Fig. 3 have been quite accurate in estimating static formation temperature as demonstrated in the following examples.

Field Examples of Estimating Static Formation Temperature

Example 1

The following data was obtained at a specific depth after 14 hours of circulating (t_k).

T_m = Datum circulating mud temperature, 164°F.

Δt = Time since circulation stopped, 10.75 hours.

T_{ws} = Datum shut-in temperature at time Δt, 282°F.

Solve for Horner dimensionless time:

$$\frac{t_k + \Delta t}{\Delta t} = \frac{14 + 10.75}{10.75} = 2.30$$

From graph:

$$\frac{T_i - T_{ws}}{T_i - T_m} = .446$$

$$\frac{T_i - 282}{T_i - 164} = .446$$

$$T_i = 377^{o}F$$

The static temperature recorded at this datum several months after completion was 377°F.

Example 2

The following data was obtained at a different datum in another well after 2.22 hours of circulation (t_k):

$$T_m = 180^{o}F$$

$$t = 6.62 \text{ hours}$$

$$T_{ws} = 225^{o}F$$

$$\frac{t_k + \Delta t}{\Delta t} = 1.335$$

From graph: $\frac{T_i - 255}{T_i - 180} = .50$

$T_i = 330^{\circ}F$

The static temperature recorded at this datum more than 7 months after completion was $334^{\circ}F$.

References

(1) Timko, D. J., and Fertl, W. H.: "How downhole temperatures, pressures affect drilling," World Oil (October, 1972).

(2) Dowdle, W. L., and Cobb, W. M.: "Static formation temperature from well logs--an empirical method," J. Pet. Tech. (November, 1975) pgs. 1326-1330.

(3) Carslaw, H. S., and Jaeger, J. C.: "Conduction of heat in solids," The Clarendon Press, Oxford University (1947).

(4) Edwardson, M. J., Girner, H. M., Parkison, H. R., Williamson, C. D., and Matthews, C. S.: "Calculation of formation temperature disturbances caused by mud circulation," J. Pet. Tech. (April, 1962) pgs. 416-426, Trans., AIME, 225.

(5) Ingersoll, L. R., Zobel, O. J., and Ingersoll, A. C.: "Heat conduction," U. Wisconsin Press, Madison, Wisconsin, (1954).

Nomenclature

C_p = Specific heat capacity, Btu/lb-°F.

K = Thermal conductivity, Btu/hr-ft-°F.

r = Radial distance, feet.

r_w = Wellbore radius, feet.

r_D = r/r_w, dimensionless radius.

t_k = Circulation time, hours.

Δt = Shut-in time since circulation, hours.

T_i = Static formation temperature, °F.

T_m = Datum circulating mud temperature, °F.

T_{ws} = Datum shut-in temperature at time Δt, °F.

ρ = Density, lbs/cu ft.

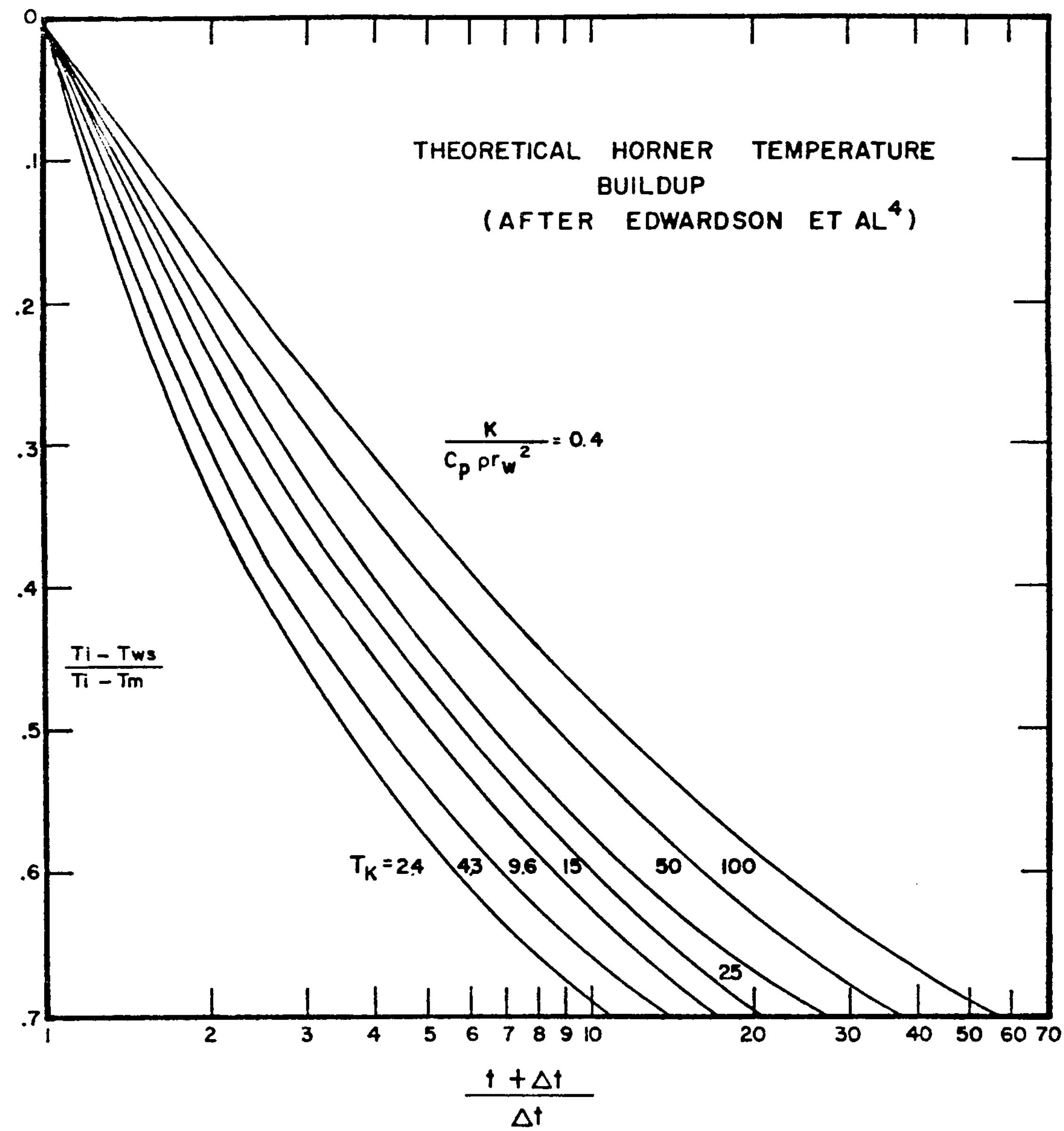
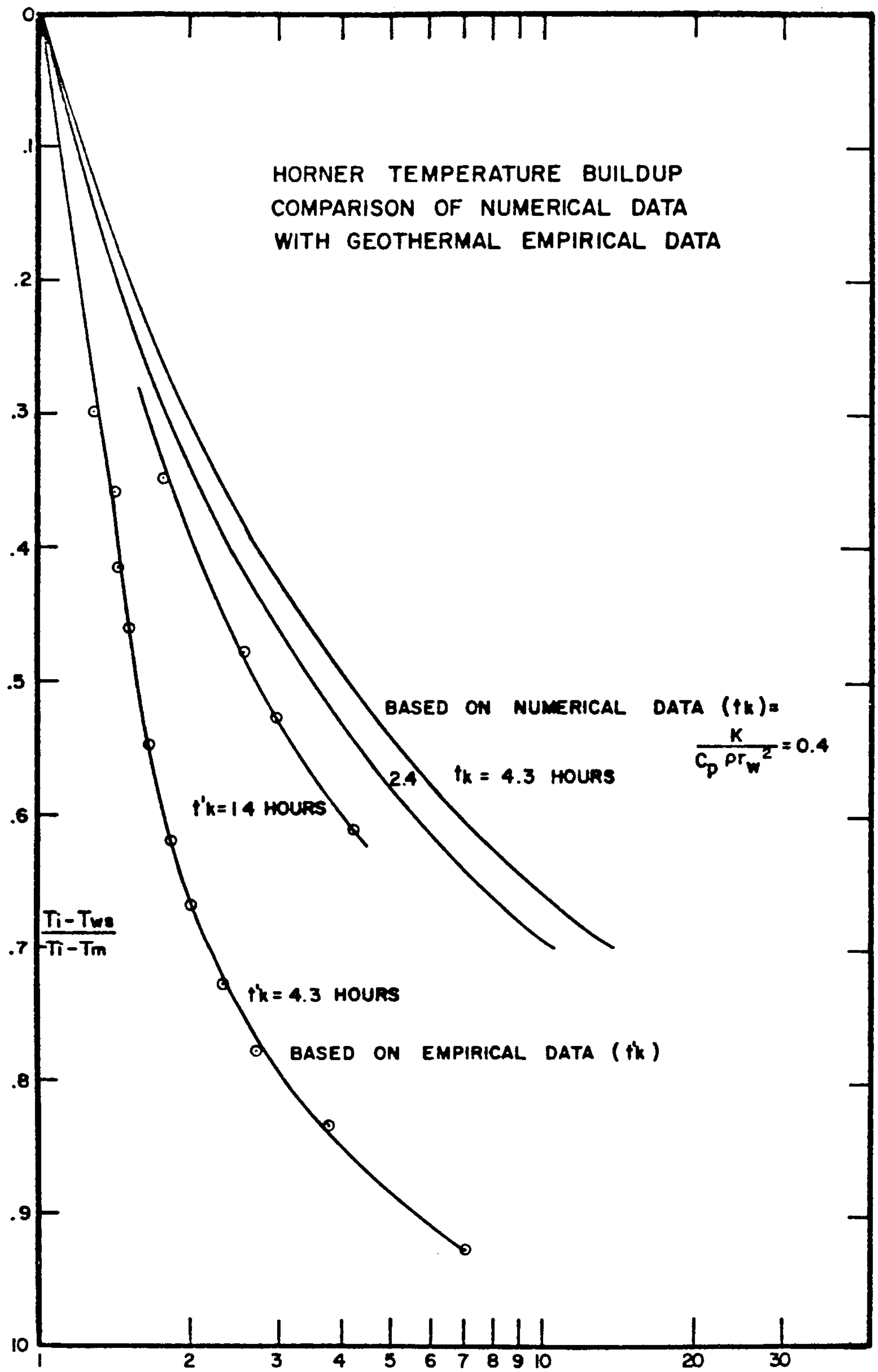
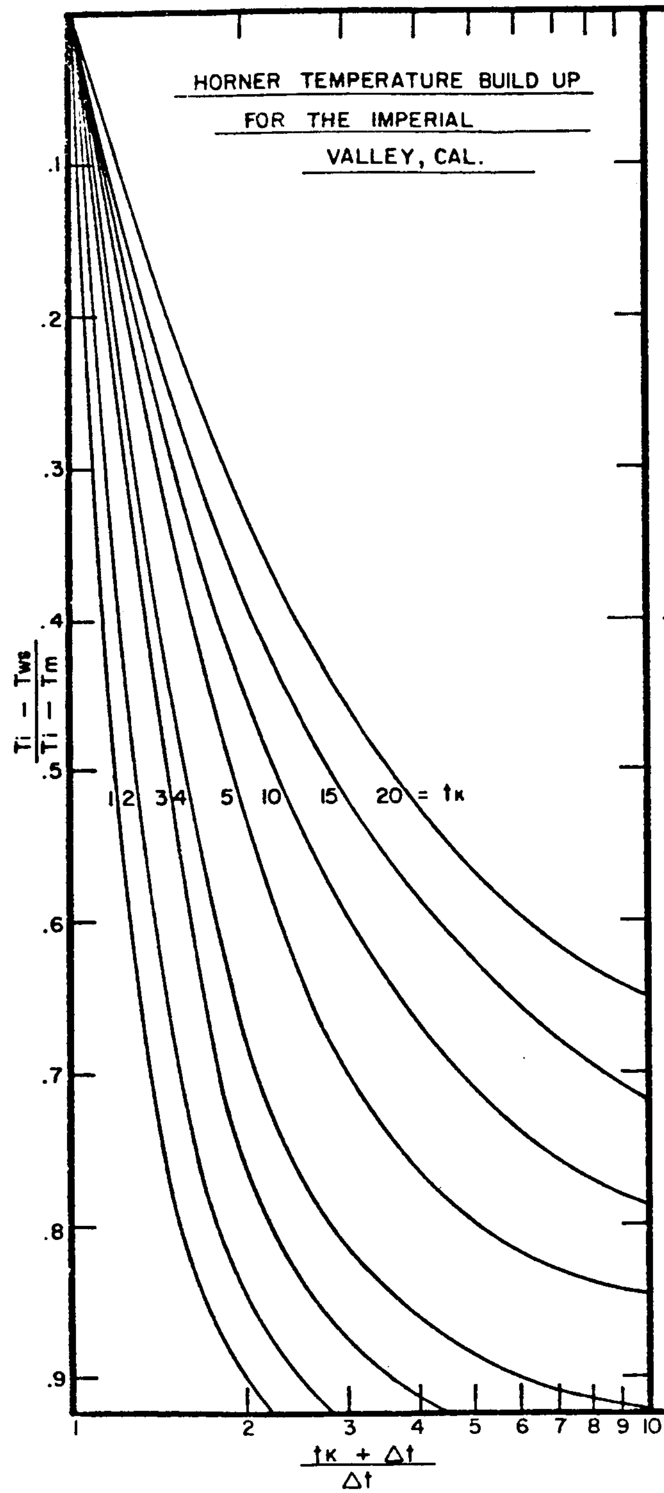

THEORETICAL HORNER TEMPERATURE BUILDUP
(AFTER EDWARDSON ET AL4)
K / Cp ρrw2 = 0.4
Ti - Tws / Ti - Tm
TK = 2.4
4.3
9.6
15
25
50
100
0
.1
.2
.3
.4
.5
.6
.7
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
t + Δt / Δt

FIGURE 1.



HORNER TEMPERATURE BUILDUP
COMPARISON OF NUMERICAL DATA
WITH GEOTHERMAL EMPIRICAL DATA
BASED ON NUMERICAL DATA (tk) =
K / Cp ρ rw² = 0.4
2.4
tk = 4.3 HOURS
t'k = 14 HOURS
t'k = 4.3 HOURS
BASED ON EMPIRICAL DATA (t'k)
Ti - Tws / Ti - Tm
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
10
1
2
3
4
5
6
7
8
9
10
20
30

FIGURE 2.



t_K = CIRCULATION TIME, HOURS

T_m = DATUM CIRCULATING MUD TEMP, °F

T_{ws} = DATUM SHUT IN TEMP. AT TIME Δt, °F

Δt = SHUT IN TIME, HRS.

T_i = STATIC FORMATION TEMP, °F

ESTIMATION OF STATIC FORMATION TEMPERATURE

PROCEDURE:

1. CALCULATE $\frac{t_K + \Delta t}{\Delta t}$
2. ENTER GRAPH AT $\frac{t_K + \Delta t}{\Delta t}$ AND PROCEED VERTICALLY TO THE INTERSECTION OF THE PROPER t_K CURVE. READ THE VALUE FOR $\frac{T_i - T_{ws}}{T_i - T_m}$ ON THE ORDINATE SCALE CORRESPONDING TO THE INTERSECTION
3. SOLVE FOR T_i

FIGURE 3.