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DESIGNING AN INTERFERENCE WELL TEST IN A GEOTHERMAL RESERVOIR

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ABSTRACT

A new technique has been developed for determination of the formation permeability, hydraulic diffusivity, and the porosity-total compressibility product from interference well tests in geothermal reservoirs. At present curve-matching technique (where only values of several pressure drops are used for matching) is utilized to process field data. A new method of field data processing, where all measured pressure drops are utilized, is proposed. It is also shown that when high precision (resolution) pressure gauges are employed the pressure time derivative equation can be used for determination of formation hydraulic diffusivity. One example of designing an interference test is presented. A field example is presented to demonstrate the data processing procedure.

INTRODUCTION

The standard drawdown and buildup pressure well tests are used to determine the formation permeability and to estimate to what degree (expressed through skin factor) the drilling and production operations altered the permeability of formations near the wellbore. To process the field data the formation porosity (φ) - total compressibility (c_t) product should be known. These parameters cannot be determined from a pressure or flow test in a singular well. Only from interference tests (multiple-well tests) the value of φc_t can be estimated. The name comes from the fact that the pressure drop caused by the producing wells at the closed observational well "interferes with" the pressure at observational well (Matthews and Russell, 1967). At interference testing at least two wells are used: one well (the "active" well) is put on production or injection, and in the second "observational" well the pressure changes are observed during production (injection) and shut-in of the first well. The pressure response in the "observational" well, allows to estimate the thickness (h) – formation permeability (k) product (reservoir transmissivity) and the hydraulic diffusivity of formations (η). After the value of η is determined the formation porosity – total compressibility product can be estimated. To process interference test data the type-curve matching technique is used (Earlougher, 1977; Horne, 1995). This technique is based on the assumption that during production (or injection) the radial flow behavior in an infinite gomogeneous reservoir can be expressed by the Ei function – the exponential integral. The set of data obtained after shut-in of the "active" well can be matched to a special form of the exponential integral or line source type curve developed by Dr. Henry J. Ramey, Jr. (Horne, 1995). The disadvantage of the type-curve matching technique is that, usually, only several values of pressure drops can be used. For example, in a field case (please see below) only values of four pressure drops can be used at curve matching (Earlougher, 1977). It should be also noted that pressure drops can be very small over distance and high accuracy electronic gauges should be utilized to monitor the pressure changes in the "observational" well. In this paper we suggests a more effective method for processing results of well interference tests. The basic equation (the exponential integral) remains the same. However, *all pressure drops points* can be used to obtain averaged values of φc_t, kh and η. Below we will also show that in some cases (when high resolution electronic gauges are used) the time derivative of the transient pressure can be utilized at designing an interference well test. We should to note that interpretation results of standard drawdown and buildup pressure well tests have been enhanced by the use of derivative plots (e.g., Bourdet et al., 1989; Horne, 1995). In this study we will consider only geothermal reservoirs where the water temperatures are below 100 ^{o}C.

WORKING EQUATIONS

At present the oilfield (practical) units are usually used to measure and process field data. The dimensions of the parameters are: the flow rate [q] = standard barrel per day (STB/D), volume formation factor [B] = RB/STB, formation permeability [k] = mD (milliDarcy), pressure [p] = psia (pound-force per squared inch), time [t] = hr, production (injection) time [t_p] = hr, formation thickness [h] = ft, dynamic viscosity [μ] = cp, total compressibility [c_t] = 1/psia, well radius [r_w] = ft, radial distance [r] = ft, distance between the "active" and "observational" wells [R] = ft, porosity [ϕ] = fraction, and hydraulic diffusivity [η] = ft^2/hr. STB is one barrel at standard conditions (p = 14.7 psia T = 60^{o}F) and RB is one barrel at reservoir pressure and temperature. For $r = R$ and $t < t_p$ (Matthews and Russell, 1967).

$$p_i - p_w(R,t) = -M\,Ei\left(-\frac{D}{t}\right) \quad (1)$$

$$D = \frac{R^2}{4\eta} \quad (2)$$

$$M = 70.6\frac{q\mu B}{kh} \qquad \eta = \frac{0.0002637k}{\phi c_t \mu} \quad (3)$$

where p_i is the initial pressure and p_w is the bottom-hole pressure at the "observational" well.

For $r = R$ and $t > t_p$

$$p_i - p_{ws}(R,t) = M\left[-Ei\left(-\frac{D}{t}\right) + Ei\left(-\frac{D}{t-t_p}\right)\right] \quad (4)$$

where p_{ws} is the bottom-hole pressure at the "observational" well after shut-in of the "active" well. Below we will also show that the time derivative of p_{ws} can be utilized at designing an interference test. The differentiation of the last equation yields

$$p^{\bullet}_{ws}(R,t) = \frac{dp_{ws}}{dt} = \frac{M}{t-t_p}\exp\left(-\frac{D}{t-t_p}\right) - \frac{M}{t}\exp\left(-\frac{D}{t}\right) \quad (5)$$

Let us now assume that at some time $t = t_x$ the pressure drop at the observation well reaches its maximum value. Then p_{ws}* = 0, and from the last equation we obtain

$$\ln\frac{t_x}{t_x - t_p} = D\left(\frac{1}{t_x - t_p} - \frac{1}{t_x}\right); \qquad \Delta t_x = t_x - t_p \quad (6)$$

Thus, by specifying the parameter D, we can evaluate the time when the maximum pressure drop occurs at the observation well.

At least two measurements of transient pressure at the observation well (at time $t = t_1$ and $t = t_2$) are needed to calculate the coefficient of hydraulic diffusivity, formation permeability, and the total compressibility-porosity product. Let

$$p_i - p_w(R, t = t_1) = -M\,Ei\left(-\frac{D}{t_1}\right) \quad (7)$$

$$p_i - p_w(R, t = t_2) = -M\,Ei\left(-\frac{D}{t_2}\right) \quad (8)$$

Then the pressure ratio is

$$\psi = \frac{p_i - p_w(R, t = t_1)}{p_i - p_w(R, t = t_2)} = \frac{Ei\left(-\frac{D}{t_1}\right)}{Ei\left(-\frac{D}{t_2}\right)} = f(D) \quad (9)$$

Let's assume that the absolute accuracy of the ratio ψ is ε, then solving the following equation we calculate the value of D

$$\psi - f(D) = \varepsilon \quad (10)$$

The Newton's method was used for solving Eq. (10) (Grossman, 1977). In this method a solution of an equation is sought by defining a sequence of numbers which become successively closer and closer to the solution. The conditions, which guarantee that Newton's method in our case will work and provide a unique solution, are satisfied (Grossman, 1977, p.259). The selection of the parameter ε (Eq. 10) is determined by the relative error of the ratio ψ (Eqs. (9) and (10)). For example, if the value of the relative error $\Delta\psi/\psi$ is 0.001, then ε = 0.001. Note that if N records of pressure drops are available, it is possible to obtain $N\cdot(N\text{-}1)/2$ values of D. In this case the regression technique can be used to analyze test data.

From Eqs. 7 or 8 we can calculate the parameter M and, hence, the value of formation permeability

$$k = 70.6\frac{q\mu B}{Mh} \quad (11)$$

The coefficient of hydraulic diffusivity and the total compressibility-porosity product can be determined from Eqs. 2 and 3

$$\eta = \frac{R^2}{4D}; \qquad \phi c_t = \frac{0.0002637k}{\eta\mu} \quad (12)$$

DRAINAGE RADIUS

Presented solutions of the diffusivity differential equation are valid only for the transient (infinite-acting reservoir) period. This means that during the test the pressure field around the borehole is practically not affected by reservoir's boundaries or by others production (injection) wells. Therefore, in order to estimate the duration of the transient period, the drainage radius should be determined with a sufficient accuracy. It is desirable to have an approximate relationship between dimensionless cumulative production and dimensionless time (e.g., Kutasov and Hejri, 1984; Johnson, 1986). We used the material balance condition to determine the well drainage radius. For a well produced at a constant flow rate (Eppelbaum and Kutasov, 2006). It was found that the following equation could be used to estimate the dimensionless drainage radius as a function of dimensionless production or injection time

$$t_D = \frac{1}{4}\frac{R_{dr}^2 - 2.\ln(R_{dr}) - 1}{\ln(R_{dr})}\cdot\ln\left[1+\left(c-\frac{1}{a+\sqrt{t_D}}\right)\sqrt{t_D}\right] \quad (13)$$

where

$$\left\{\begin{array}{l} t_D = \dfrac{kt}{\phi c_t \mu r_w^2}; \\ R_{dr} = \dfrac{r_{dr}}{r_w}; \\ a = 2.7010505; c = 1.4986055 \end{array}\right\} \quad (14)$$

It should be noted that here dimensionless time is based on the active well radius and the values of t_D are very large. Calculations after Eq. 13 show that the function $R_{dr} = f(t_D)$ can be approximated by a simple formula

$$R_{dr} = 1 + d\sqrt{t_D} \quad (15)$$

For $10^3 < t_D < 10^{16}$ the values of d vary from 2.053 to 2.017 (for $t_D = 10^{16}$), and therefore, for practical purposes, we can assume that

$$R_{dr} \approx 2\sqrt{t_D} \quad \text{or} \quad r_{dr} \approx 2\sqrt{\eta t} \quad (16)$$

TEST DESIGNING EXAMPLE

At designing an interference well test the preference should be given to a producing "active" well rather than to an injection well. The application of the above mentioned working equation requires that the physical properties of the injected fluids (dynamic viscosity, compressibility, volumetric thermal expansion) are the same as the properties of the reservoir fluids. For example, viscosity of water is very much dependent on the temperature. Thus the mobility (formation permeability–viscosity ratio) of the injected water should be very close to that of the reservoir water. The transient test analysis for an injection well with non-unit mobility ratio is complex and the reservoir should be considered as a composite system (Earlougher, 1977). Let us assume that during interference test water with temperature of 80 °C (176 °F) was produced in Well 1 for 50 hours. The pressure response in Well 2, 150 ft away, was observed for 100 hours. Known and estimated reservoir properties are presented in Table 1.

Table 1. Reservoir data

h = 20 ft	depth = 4,920 ft
t_p = 50 hours	μ = 0.355 cp
q = 400 STB/D	R = 150 ft
B = 1.014 RB/STB	p_i = 649.74 psia
c_t = (3.0-4.5)·10^{-5} 1/psia	φ = 0.2 – 0.3
T = 176 °F	k = 100 mD – 150 mD

We assumed that the values φ, c_t, and k might vary in some intervals (Table 1). The value of dynamic viscosity was taken from Table 2.

Table 2. Dynamic viscosity of water (Internet: http://www.engineeringtoolbox.com)

T, °C	μ, cp	T, °C	μ, cp	T, °C	μ, cp
0	1.78	35	0.719	70	0.404
5	1.52	40	0.653	75	0.378
10	1.31	45	0.596	80	0.355
15	1.14	50	0.547	85	0.334
20	1.00	55	0.504	90	0.314
25	0.890	60	0.467	95	0.297
30	0.798	65	0.434	100	0.281

The water formation volume factor (B) was calculated from the following equation (Kutasov, 1989):

$$B = 0.998\exp[-\alpha p - \beta(T - T_s) - \gamma(T - T_s)^2] \quad (17)$$

where pressure is in psig, temperature in °F, T_s = 59 °F and

α = 2.7384E-06 1/psig,

β = -1.5353E-04 $°F^{-1}$, γ = -7.4690E-07 $°F^{-2}$

The maximum and minimum values of the hydraulic diffusivity coefficient are

$$\eta = \frac{0.0002637\cdot 150}{0.20\cdot 3\cdot 10^{-5}\cdot 0.355} = 18{,}570\left(\frac{ft^2}{hr}\right)$$

$$\eta = \frac{0.0002637\cdot 100}{0.30\cdot 4.5\cdot 10^{-5}\cdot 0.355} = 5{,}502\left(\frac{ft^2}{hr}\right)$$

The corresponding values of the parameter D are:

$$D = \frac{150^2}{4\cdot 18{,}570} = 0.3029 \text{ (hrs)}$$

$$D = \frac{150^2}{4\cdot 5{,}502} = 1.0223 \text{ (hrs)}$$

The pressure drops in the observational well and values of Δt_x were calculated after Eqs. 1, 4 and 6 are presented in Table 3.

Table 3. The pressure drops and values of Δt_x

t, hours	D = 1.0223, Δt_x = 0.1811, hours	D = 0.3029, Δt_x = 0.0429 , hours
	Δp, psia	Δp, psia
3.0	4.13	6.15
5.0	6.12	7.75
10.0	9.17	10.00
20.0	12.44	12.30
30.0	14.42	13.65
40.0	15.84	14.62
49.9	16.94	15.36
50.1	16.96	15.34
51.0	15.97	12.39
60.0	8.69	5.99
70.0	6.19	4.21
80.0	4.88	3.30
90.0	4.05	2.73
100.0	3.47	2.34

Thus the predicted values of the pressure drops will be within of the 0-17.0 psia interval. How it will be shown in the next Section, to determine with high accuracy (from monitoring the pressure drops in the observational well) values of Δt_x, pressure gauges with high limiting precision (resolution) are needed.

FIELD CASE

During an interference test, water was injected into Well A for 48 hours. The pressure response in Well B, 119 ft away, was observed for 148 hours. Known reservoir properties are presented in Table 4 (Earlougher, 1977, Example 9.1).

Table 4. Reservoir data, field case

h = 45 ft t_p = 48 hours q = -170 STB/D B = 1.0 RB/STB $c_t = 9.0 \cdot 10^{-6}$ 1/psia	depth = 2,000 ft μ = 1.0 cp R =119 ft p_i = 0 psig

The observed pressure and the flow hystory are presented in Table 5 and Fig. 1

Table 5. Interference test data for the field example

t, hours	p_w, psig	$\Delta p = p_i - p_w$, psia
0.0	0	-
4.3	22	-22
21.6	82	-82
28.2	95	-95
45.0	119	-119
48.0	Injection ends	
51.0	109	-109
69.0	55	-55
73.0	47	-47
93.0	32	-32
142.0	16	-16
148.0	15	-15

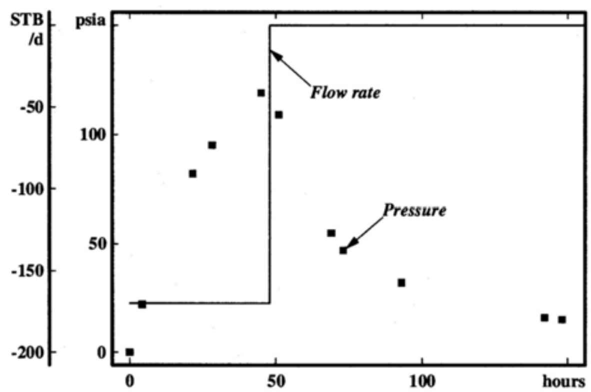

Figure 1. Observed pressure and flow history (Horne, 1995)

Earlougher (1977) used the curve-matching method and also have analyzed the data by three different computer-aided techniques. It was and found that it would probably be best to use k = 5.7 mD and $\varphi c_t = 0.99 \cdot 10^{-6}$ 1/psia. The parameter D is

$$D = D_E = \frac{119^2 \cdot 0.99 \cdot 10^{-6} \cdot 1.0}{4 \cdot 0.0002637 \cdot 5.7} = 2.331(\text{hrs})$$

Horne (1995) analyzed the same field data and for the matching point at t = 24 hours the values of k = 5.507 mD, φ = 0.109 were determined, and

$$D = D_H = \frac{119^2 \cdot 0.109 \cdot 9 \cdot 10^{-6} \cdot 1.0}{4 \cdot 0.0002637 \cdot 5.507} = 2.392(\text{hrs})$$

We used time pairs 4.3-21.6 hrs, 4.3-28.2 hrs and 4.3-45.0 hrs (Table 5) and from Eqs. 10,7 and 12 computed the squared averaged values: k =5.222 mD, and φ = 0.109. Then

$$D = D_{KE} = \frac{119^2 \cdot 0.117 \cdot 9 \cdot 10^{-6} \cdot 1.0}{4 \cdot 0.0002637 \cdot 5.222} = 2.707(\text{hrs})$$

Now the shut-in time at which the maximum pressure drop occurs can be determined from Eq. 6 (Fig. 2).

The transient pressure drops were calculated (Eqs. 1 and 4) for three sets of parameters (k, φc_t) obtained by Earlougher (1977), Horne (1995) and by the authors.

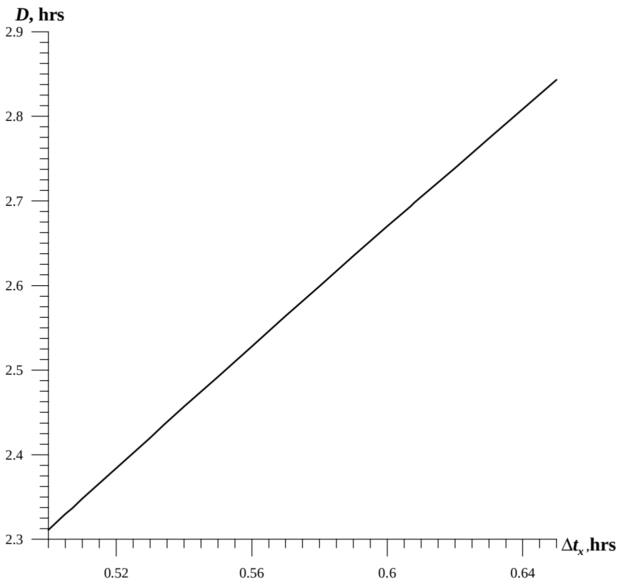

Figure 2. The $D = D(\Delta t_x)$ *dependence for the field example*

The pressure drops are denoted as Δp_E, Δp_H and Δp, correspondingly (Table 6).

Table 6. Comparison of observed pressure changes, Δp^*, with calculated pressure drops (Δp_E, Δp_H, Δp)

t, hours	Δp^*, psia	Δp_E, psia	Δp_H, psia	Δp, psia
4.3	22	23.9	24.0	22.0
21.6	82	82.1	83.7	83.0
28.2	95	93.4	95.4	95.2
45.0	119	113.9	116.6	117.3
51.0	109	104.3	107.3	110.0
69.0	55	52.2	53.9	56.4
73.0	47	47.4	49.0	51.2
93.0	32	32.7	33.9	35.5
142.0	16	18.9	19.6	20.6
148.0	15	18.0	18.6	19.6

From Table 6 one can see that the calculated pressure drops are in satisfactory agreement (taking also into account the low accuracy of Δp^* values) with observed ones. For the parameter of $D = D_E = 2.3310$ hrs the computed (from Eq. 6) value of Δt_x is 0.5054 hrs or 30.32 min. (Fig. 2). The maximum pressure drop (after Eqs. 4) is 117.191 psia (Table 7. Now let assume that the value of Δt_x can be detected with accuracy of ±0.5 minutes and the calculated values of D (after Eq. 6) are presented in Table 7.

Conclusions

At present the type-curve matching technique is used to estimate the porosity-total compressibility product (φc_t) and formation permeability (k) from interference well tests. The disadvantage of this method is that (usually) only several values of pressure drops can be used. A more effective method for processing results of well interference tests is suggested. The basic equation (the exponential integral) remains the same. However, *all pressure drops points* can be used to obtain averaged values of φc_t and k. It is also shown that in some cases (when high resolution electronic gauges are used) the time derivative of the transient pressure can be utilized.

Table 7. The accuracy of determination of the parameter D, Δt_x = 30.32 min

$\Delta t - \Delta t_x$, minutes	Δp, psia	D, hours	D/2.3310
-5	117.170	2.0193	0.866
-4	117.177	2.0827	0.894
-3	117.183	2.1456	0.921
-2	117.187	2.2079	0.947
-1	117.190	2.2697	0.974
0	117.191	2.3310	1.000
+1	117.190	2.3917	1.026
+2	117.187	2.4520	1.052
+3	117.182	2.5118	1.078
+4	117.176	2.5711	1.103
+5	117.167	2.6301	1.128

In this case pressure gauges should have resolution of ± 0.02 psia, and even in this case the hydraulic diffusivity can be determined with the accuracy of ± 13%. It is clear that in this field example the Eq. 6 cannot be used because the accuracy of measurements is about ± 0.5 psia (Table 5).

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