Calculation of Reservoir Characteristics by the Pressure Curve at the Inflow Using Reference Curves

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Abstract. In this paper, we propose a method for calculating the filtration characteristics of the reservoir by the inflow curve obtained when the well was put into operation after creating a sharp discontinuity in the reservoir pressure drawdown. The need to improve the accuracy of determining the reservoir characteristics according to flowing tests is an urgent topic for many oil companies. The developed methodology for calculating the reservoir characteristics according to the data of the reference inflow curves differs from the well-known methods of processing the inflow curves and also determines the reservoir porosity in addition to its permeability.

1. Introduction

The inflow curves recorded by deep gauges are obtained when the well is put into operation after a sharp discontinuity in the reservoir pressure drawdown is created.

Such studies can include the processes that occur when opening the reservoir tester valve, when pressure of a fluid column in a partially filled string of drill or tubing is abruptly transferred to the reservoir. In this case, the fluid in the well is isolated from the reservoir by the packer. When creating the reservoir pressure drawdown, reservoir fluid enters the drill pipes, and the growth of the column of fluid in the pipe string increases the pressure on the reservoir. Thus, the change in the downhole pressure is captured and the inflow curve is recorded.

The same thing happens by reducing the pressure in the well by compression. When air is injected into the annulus after lowering the liquid level in the well, there is a sharp release of air on the surface. Filling a well with reservoir fluid from the reservoir is accompanied by the decrease in reservoir pressure drawdown. Downhole pressure captures the pressure growth curve, that is, the inflow curve.

2. Methods

To interpret the pressure diagrams with the free fluid inflow into the pipes after creating a sharp discontinuity in the reservoir pressure drawdown, the method of reference inflow curves can be applied obtained by solving the initial differential filtration equation:

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} = \frac{m \mu \beta}{k} \frac{\partial P}{\partial t},$$

where $P$ – pressure at the distance $r$ from the well at time $t$, $P_a$; $m$ – porosity, $Pa \cdot S$; $\beta$ – compressibility $Pa^{-1}$; $k$ – permeability, $m^2$. 

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When solving the equation (1), the following conditions are accepted:
1. The outer boundary is assumed to be infinite with the constant initial pressure on it \( P=P_0 \),
2. The inner boundary is assumed to be very small (but final) with a given initial pressure on it \( P_0 = P_w(0) \).
3. The flow rate is equal to the rate of the fluid accumulation in the well (pipes):
   \[
   q = \frac{dV}{dt},
   \]
   where \( q \) – the fluid flow rate, \( m^3/s \); \( V \)– the volume of fluid received over time \( t \), \( m^3 \).

In the general case, the downhole pressure \( P_w(t) \) is determined from the expression
\[
P_w(t) = P_w(0) + \Delta P_w(t),
\]
where \( P_w(t) \) is the pressure in the well at the time \( t \), \( Pa \); \( P_w(0) \)is pressure at the beginning of the inflow, \( Pa \); \( \Delta P_w(t) \) is the additional pressure exerted by a fluid column entering the well during the study period, \( Pa \).

The additional pressure associated with the fluid accumulation in the pipes \( \Delta P_w(t) \) can be represented as
\[
\Delta P_w(t) = \frac{V(t)}{C_T},
\]
where \( V(t) \) is the volume of fluid received over time the \( t \), \( m^3 \); \( C_T \) is a capacitive indicator characterizing the fluid increase in the pipes during the influx \( \Delta V \) per unit of pressure change in them (pipe capacity), \( \Delta P \):
\[
C_T = \frac{\Delta V}{\Delta P} = \frac{f_r h}{\gamma_n h} = \frac{\pi r_T^2}{\gamma_n};
\]
where \( f_T \) is the cross-sectional area of the internal cavity of the pipes (drill ones when working with drill-stem reservoir tester and casing ones during normal research), \( m^2 \); \( h \) is the increase in fluid in the pipes, \( m \); \( \gamma_n \) is the specific gravity of the incoming fluid, \( H/m^2 \); \( r_p \) is the internal pipe radius, \( m \).

The solution of the equation (1) has the form:
\[
P_w^* = \frac{P_r - P_w(t)}{P_r - P_w(t)} = \Phi(C_0, t_\theta),
\]
where
\[
\Phi(C_0, t_\theta) = \int_0^\infty \frac{C_0 \cdot \exp(-u^2 t_\theta)}{u \left[ u C_0 J_0(u) \right]^2 + \left[ u C_0 Y_0(u) - Y_1(u) \right]^2} \, du,
\]
here \( C_0 = \frac{C_T}{2\pi m \mu \beta r_w^2} \) is dimensionless characteristic of the well capacity; \( t_\theta = \frac{kr}{m \mu \beta r_w^2} \) is the dimensionless characteristic of the time of the reservoir study; \( k \) is the permeability, \( m^2 \); \( m \) is the porosity; \( \mu \) is the viscosity; \( Pa \cdot s \); \( h \) is the thickness of the reservoir, \( m \); \( r_w \) is the radius of the well, \( m \).

Calculation of characteristics by reference inflow curves reduces to comparing (superimposing) the real inflow curves, \( P_w = f(t) \), rebuilt on the same scale as the reference curves, and to searching for the reference curve that most fully matches it throughout its length. Then, the reservoir porosity is calculated according to the characteristic \( C_0 \) corresponding to the curve found. And the reservoir permeability is estimated according to the corresponding values on the abscissa scale \( t_\theta/C_0 \).
3. Results and discussion
As an example, let us consider the calculation of reservoir filtration characteristics and well productivity coefficients from the inflow curve obtained in the study of the well No. 2548 of the Samotlor field.

Initial data: downhole pressure (initial) is 85 bar; reservoir pressure is 185 bar; perforation interval is 1845-1856 m; effective reservoir thickness is 6.6 m; porosity is 0.2; the compressibility of the mixture is 1.1 • 10^-4 bar^-1; the rock compressibility is 1.0 • 10^-5 bar^-1; the volumetric oil coefficient 1.16; the oil viscosity in reservoir conditions is 1.06 cp; the oil density is 0.86 g/cm^3; the distance between the wells is 400 m; the radius of the tubing is 0.063 m.

1. As the well practically did not work before the “shutdown”, it is not possible to select any known calculation scheme, since in all schemes there is a prerequisite selection of fluid from the reservoir at a sampling time comparable to the time of the pressure buildup curve or over this time.

The work graph is built in coordinates \( P^* - \lg t \), where \( P^* = \frac{P_c - P_w(t)}{P_c - P_w(0)} \).

2. According to the data in Table 1, the work graph of the pressure buildup curve is plotted in the semi-logarithmic coordinates \( P(t) - \lg t \) (Figure 1) by the same scale as the graphs of the reference curves (Figure 2). The actual inflow curve is superimposed on the reference curve with parallel movement of these curves relative to each other. Along the abscissa axis there is such a curve on the reference graph, which most fully coincides with the compared curve over its entire length.

3. A correspondence is established between an arbitrarily chosen value of the actual time \( t \) on the inflow curve and the dimensionless time \( t_0 \) on the graph of the reference curves.

For \( t_0/C_0 = 10^6 \), the corresponding value is \( t = 10^n583 \approx 38312 \) s.

**Table 1.** Pressure-time data obtained after processing the pressure diagram.

| \( N \) | \( P_c, \text{ am} \) | \( T, \text{ h} \) | \( P_c, \text{ bar} \) | \( T, \text{ h} \) | \( \text{No.} \) | \( P_c, \text{ bar} \) | \( T, \text{ h} \) |
|-------|----------------|--------|----------------|--------|----------|----------------|--------|
| 1     | 87.5           | 2      | 18             | 128.3  | 43.7     | 35             | 159    | 75.2          |
| 2     | 90.0           | 5      | 19             | 131.2  | 46.6     | 36             | 160    | 75.6          |
| 3     | 92.0           | 7      | 20             | 134.0  | 49.4     | 37             | 161    | 76.9          |
| 4     | 95.0           | 10     | 21             | 137.3  | 52.7     | 38             | 162    | 77.7          |
| 5     | 98.0           | 13     | 22             | 139.4  | 54.8     | 39             | 163    | 79.1          |
| 6     | 100.5          | 15     | 23             | 141.5  | 56.9     | 40             | 163    | 79.1          |
| 7     | 102.5          | 17     | 24             | 143.5  | 58.9     | 41             | 164    | 79.8          |
| 8     | 104.3          | 19     | 25             | 145.5  | 60.9     | 42             | 165    | 80.5          |
| 9     | 106.0          | 21     | 26             | 147.5  | 62.9     | 43             | 165    | 81.1          |
| 10    | 107.8          | 23     | 27             | 149.3  | 64.7     | 44             | 166    | 81.7          |
| 11    | 109.2          | 24     | 28             | 150.9  | 66.3     | 45             | 166    | 82.2          |
| 12    | 112.0          | 27     | 29             | 152.5  | 67.9     | 46             | 167    | 82.7          |
| 13    | 114.5          | 29     | 30             | 154.0  | 69.4     | 47             | 167    | 83.0          |
| 14    | 117.4          | 32     | 31             | 155.3  | 70.7     | 48             | 168    | 83.4          |
| 15    | 120.0          | 35     | 32             | 156.5  | 71.9     | 49             | 168    | 83.5          |
| 16    | 122.7          | 38     | 33             | 157.8  | 73.2     | 50             | 168    | 84.0          |
| 17    | 125.5          | 40     | 34             | 159.0  | 74.4     | 51             | 168    | 84.2          |
Figure 1. Working graph of the inflow curve in the well No. 2548 of the Samotlor field.

Figure 2. Interpretation of the pressure buildup equation recorded at the well test in the well No. 2548.

In Figure 2 such a procedure is shown. The compared curve matches the reference curve 10 most closely corresponding to $C_0 = 10^6$.

4. The hydraulic conductivity of the reservoir is determined by the formula:
\[
\frac{kh}{\mu} = \left( \frac{t}{C_P} \right) \cdot r_T^2 = \left( \frac{t}{C_P} \right) \cdot r_T^2 = \left( \frac{t}{C_P} \right) \cdot \frac{0.063^2 m^2}{2 \cdot 38312 s \cdot 0.86 \cdot 10^3 kg/m^3 \cdot 9.81 m/s^2} = \frac{0.063^2}{2 \cdot 38312 \cdot 860 \cdot 9.81} \cdot \frac{m^3}{Pa \cdot s} = 6.14 \cdot 10^{-12} \frac{m^3}{Pa \cdot s}.
\]

5. The reservoir permeability:
\[
k = \left( \frac{kh}{\mu} \right) h = \frac{6.14 \cdot 10^{-12} \frac{m^3}{Pa \cdot s} \cdot 1.06 cP}{6.6m} = \frac{6.14 \cdot 10^{-12} \cdot 1.06 \cdot 10^{-3} m^2}{6.6} = 0.986 \cdot 10^{-15} m^2.
\]

6. The coefficient of piezo-conductivity:
\[
\chi = \frac{k}{\mu(m \beta_m + \beta_c)} = \frac{0.986 \cdot 10^{-15} m^2}{1.06 \cdot 10^{-3} Pa \cdot c \cdot (0.2 \cdot 1.1 \cdot 10^{-4} bar^{-1} + 10^{-5} bar^{-1})} = \frac{0.986 \cdot 10^{-15} m^2}{1.06 \cdot 10^{-3} Pa \cdot c \cdot (0.2 \cdot 1.1 \cdot 10^{-9} Pa^{-1} + 10^{-10} Pa^{-1})} = 0.0029.
\]

7. The productivity factor:
\[
\eta = \frac{kh}{\mu} = \frac{6.14 \cdot 10^{-12} \frac{m^3}{Pa \cdot s} \cdot 10^3}{0.366 \cdot 10^5 \frac{m}{s}} = 0.444 \frac{m^3}{day} \frac{mPa}{mPa}.
\]

It should be noted that the usual calculation of the reservoir characteristics with the construction of the inflow curve (in the adopted methods – the pressure buildup curve) in the coordinates “pressure – logarithm of time” and using the tangent method gives a hydraulic conductivity of \(0.6 \cdot 10^{-12} m^3 / (Pa \cdot s)\), which is 10 times less than the hydraulic conductivity calculated from the graphs of the reference curves.

It should also be noted that the compared curve in the considered example clearly coincided with the reference curve only in the interval of relative pressure \(P^*\) from 1 to 0.4.

In Figure 2 reference inflow curves \(P^* = \Phi(C_t, t_t)\) are shown.

In the interval \(P^*\) from 0.4 to 0.2, the actual inflow curve deviates from the selected reference curve in the direction of the adjacent reference curve, which corresponds to the well capacity 10 times smaller than the selected curve. In this example, the capacitive index began to decrease due to the fact that the compressible gas in the annulus located above the liquid level in the well led to a decrease in the effect of after flow. In this example, the transition of the actual curve from one reference curve to another is associated not with a change in the inclination of the well, but with the manifestation of the effect of gas compression in the annulus.

4. Conclusion
The proposed methodology for processing the inflow curves requires, before finding the most suitable matching curve on the graph of the reference curves, first to “divide” the actual curve into separate sections corresponding to the movement of the fluid level in the annulus along some or other sections of the curved borehole. And it is precisely taking into account the features of the obtained inflow...
curves that the most coincident intervals of the reference curves are selected corresponding to the intervals of the work schedule.

The developed methodology for calculating the reservoir characteristics from the data of the reference inflow curves allows, in addition to the permeability of the reservoir, to determine its porosity, which compares favorably with all known methodologies for processing the inflow curves.

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