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Design and analysis of single pulse tests

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ABSTRACT

A procedure is developed for the design and analysis of single pulse tests. A new definition is adopted for the pressure response amplitude that eliminates the effect of pressure trend. The method is applicable for homogeneous reservoirs with negligible well bore storage and skin at both wells. The test may be performed in an interactive way. Analytical equations are derived that explicitly relate the dimensionless pulse time and dimensionless pressure response amplitude to the time lag ratio. This makes it possible to analyze the results automatically by a computer. Correlation charts are also presented for graphical analysis of test results. The charts are independent of the pulse ratio since it is not a parameter in the developed analytical equations. The time and pressure response amplitude are used to calculate the inter-well transmissibility kh/μ and storativity $h\phi c_t$ using graphical or analytical procedures. The effect of past production is also investigated. Past production is found to increase the estimated value of transmissibility but has little effect on the value of storativity.

1. Introduction

Pulse testing is an interference test (multiple wells) in which an active well and one or more observation (responding) wells are used in the test. The flow rate is controlled at the active well while the pressure response is recorded at the observation wells. These tests are used to verify communication between wells and to estimate inter-well properties. Reservoir anisotropy and heterogeneity can also be detected by such tests when different observation wells are used. By performing the tests at different times, the movements of different fluid banks can be monitored. This is important in secondary and enhanced oil recovery projects.

During a conventional interference test, the flow rate is kept constant at the active well while the pressure change is monitored at the observation wells. Background noise and measurement errors may affect the results of test analysis. In pulse testing, the rate at the active well is changed alternately between flow and shut-in conditions. This results in an oscillating component of the pressure response that can be easily identified for analysis. This is usually done by the tangent construction method to separate the oscillating component from the general trend of the pressure response. The time lags and pressure response amplitudes for different pulse cycles are determined from a plot of ΔP vs. t on a normal scale (Johnson et al., 1966). These parameters are related to the transmissibility $T = kh/\mu$ and the storativity $S = h\phi c_t$. The analysis is based on the exponential integral solution of the diffusivity equation for homogeneous infinite reservoir and the use of the principle of superposition to handle the variable flow rate. Correlation charts to estimate reservoir properties from the time lag and pressure response amplitude were presented for equal (Brigham, 1970) and unequal pulse and shut-in periods (Kamal and Brigham, 1976). These correlation charts are constructed by solving a set of nonlinear equations numerically using an iterative procedure. The iterative methods may face convergence problems and the results will depend on the initial guess and convergence criteria. This may make the results unreliable. Such problems were reported by Ogbe and Brigham (1987). Also the time lag may lie outside the specific pulse or shut-in period making it necessary to add an extra superposition term to the corresponding equation as was pointed out by El-Khatib (1990, 1991). Furthermore, the manual plotting of parallel tangents and the necessity of using correlation charts make the results of this method questionable. These factors make it desirable to find an alternative method that avoids the complexity and unreliability of the tangent construction method.

Johnson et al. (1966) discussed the use of a single pulse test for the estimation of transmissibility and storage. It was also outlined by Raghavan (1993) and Streltsova (1988). As presented by those authors, the single pulse test uses the point of maximum pressure response. Finding the time of this point is simple and is obtained by equating the pressure derivative to zero. Because the pressure derivative involves exponential functions rather than the exponential integral functions, an explicit analytical solution for the time lag can be obtained. However, the use of the absolute value of the maximum pressure to correlate with reservoir properties introduces an error due to the effect of past production history. Min et al. (1988) presented a single pulse test method that eliminates the trend effect by using a set of parallel straight lines. The method however is complex and does

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not provide general correlations and solutions must be obtain for the selected straight lines.

In this work, a method is presented to correct for the past pressure trend while utilizing the simplicity of the single pulse test. We introduce a new terminology for the pressure response amplitude. This method is similar to the tangent construction methods but the points used for determining pressure response amplitude are determined directly from the data. We take the difference between the maximum pressure and the pressure at the same time on a line connecting two points on both sides and at equal time intervals from the point of maximum pressure. The developed method can also be used for single pulse tests as well as for the analysis of the first pulse of a multiple pulse test.

2. Definitions and terminology

A single pulse test consists of a single cycle of duration Δt_c comprising a flow (pulse) period of Δt_p and a shut-in period of $\Delta t_s = \Delta t_c - \Delta t_p$. The flow rate during the pulse period is kept constant at q STB/day. The time at which the pressure response at the observation well attains its maximum value is denoted as t^*. The time lag t_l is given by

$$t_l = t^* - \Delta t_p \tag{1}$$

The time lag ratio x is defined as

$$x = t_l / \Delta t_p = t^* / \Delta t_p - 1 \tag{2}$$

The pressure response is determined at three points A, B, and C as shown in Fig. 1. Point A is at the end of the pulse period at time Δt_p, point B is that of maximum pressure at time t^*, and point C is at a time of $t^* + t_l$. The pressure response amplitude Δp is taken as the difference between the maximum pressure at point B and the pressure at the midpoint of the line joining points A and C.

$$\Delta P = P_B - (P_A + P_C) / 2 \tag{3}$$

This definition of the pressure response amplitude will eliminate the pressure trend effect if the trend is assumed linear with time. The duration of the shut-in period after point C has no effect on the test results. The active well can be returned to production after that point at any desirable rate.

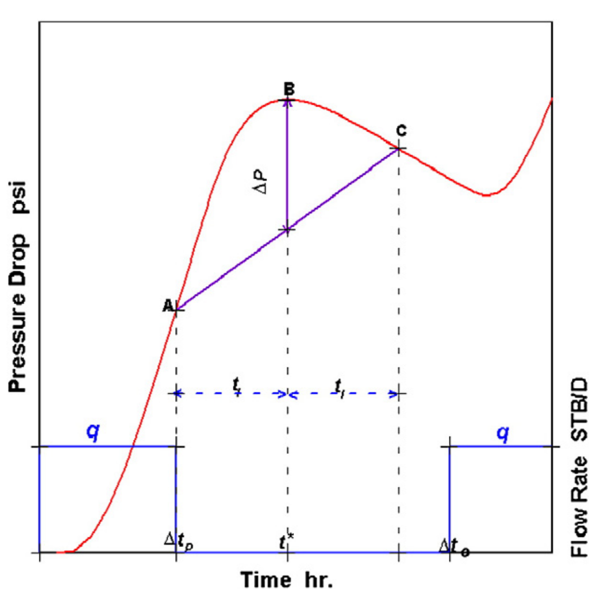

Fig. 1. Terminology for single pulse test analysis.

3. Theory

The line source solution of the diffusivity equation for an infinite homogeneous reservoir with constant production rate at the active well is applied. The pressure drop at an observation well at distance r from the active well is given by

$$\Delta P(t) = -\frac{70.6q\mu B}{Kh} Ei\left(-\frac{948\mu c\phi r^2}{Kt}\right) \tag{4}$$

In dimensionless form, the solution is

$$\Delta P_D = -\frac{1}{2} Ei\left(-\frac{1}{t_D}\right) \tag{5}$$

where

$$P_D = \frac{T\Delta P}{141.3qB} \tag{6}$$

$$t_D = \frac{Tt}{948Sr^2} \tag{7}$$

where the transmissibility T and storativity S are defined as

$$T = k\,h / \mu \tag{8}$$

$$S = h\,\phi\,c_t. \tag{9}$$

It is to be noted that the definition of the dimensionless time t_D as given by Eq. (7) is different from the conventional definition of t_{Dw} in that it is multiplied by 4 and is relative to the distance r rather than the well radius r_w. So

$$t_D = \frac{4t_{Dw}}{r_D^2}. \tag{10}$$

Applying the principle of superposition and using the terminology of Fig. 1, we can write the dimensionless pressure at point B as

$$P_D(B) = -\frac{1}{2}\left\{Ei\left(-\frac{1}{\Delta t_{pD}(1+x)}\right) - Ei\left(-\frac{1}{\Delta t_{pD}x}\right)\right\} \tag{11}$$

Taking the derivative of P_D(B) w.r.t. x and equating to zero, we get the equation for x at the point of maximum pressure which can be arranged as

$$\Delta t_{PD} = \frac{1}{x(1+x)\ln(1+1/x)} \tag{12}$$

Eq. (12) can be solved explicitly for Δt_{PD} in terms of the time lag ratio x. This is convenient since the time lag is the measured quantity in the test and Δt_{PD} is to be calculated and used for test analysis.

The dimensionless pressure at points A and C of Fig. 1 are given by

$$P_D(A) = -\frac{1}{2} Ei\left(-\frac{1}{\Delta t_{pD}}\right) \tag{13}$$

$$P_D(C) = -\frac{1}{2}\left\{Ei\left(-\frac{1}{\Delta t_{pD}(1+2x)}\right) - Ei\left(-\frac{1}{2\Delta t_{pD}x}\right)\right\} \tag{14}$$