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Perforation Inflow Test Analysis (PITA)

N. M. A. RAHMAN
Fekete Associates Inc.

M. POOLADI-DARVISH
University of Calgary

L. MATTAR
Fekete Associates Inc.

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Abstract

Due to economics or time constraints, well-testing is sometimes reduced to perforating a well under-balanced, and analyzing the inflow characteristics. The objective of a Perforation Inflow Test Analysis (PITA) is to estimate the initial reservoir pressure, permeability and skin, immediately after perforating the well. This information can be used for evaluating future development strategy. However, special analytical procedures are required for analyzing the data, because these perforation inflow tests are shorter than conventional well tests and the influx rates are not measured.

In this study, the working equations for analyzing these short tests are presented, and the procedure required for calculating meaningful estimates of the reservoir parameters is presented. Analyses of early-time and late-time data are the two major components of this approach. The early-time analysis is used for estimating the skin, and the late-time analysis is used for estimating the initial pressure and permeability. A distinctive feature of the PITA is that it does not require calculation of the influx rates, which are generally not available during a perforation test. A special derivative, called the impulse derivative, can be used to determine if the data collected is sufficient to yield meaningful results from a PITA. It is particularly important that the reservoir-dominated flow regime be reached, if the estimates of initial reservoir pressure, permeability and skin are to be acceptable. Good estimates of these parameters from a PITA will minimize the uncertainty associated with non-uniqueness in inverse problems, when modeling the test data.

Introduction

Conventional well tests have served the petroleum industry faithfully for decades as the primary and most reliable means of:

- quantifying deliverability,
- characterizing the reservoir,
- collecting reservoir fluid samples, and
- evaluating the condition of the well.

However, for the last few years, oil and gas producers have been searching for alternatives that could yield the desired information in less time, in a more environmentally-friendly manner, and at a cheaper cost than from conventional well tests. The trend has inevitably been towards tests of shorter duration. Although it is accepted that results from short tests with small radii of investigation may not be as reliable as those from conventional well tests, it is reasonable to accept that they could be of value in assisting with strategic decisions about field development, when an increased margin of error can be tolerated.

In offshore wells, in addition to the potentially exorbitant cost of testing (several millions of dollars), the drive towards green (shorter) tests is fuelled by environmental considerations, such as requirements for restricted flaring of hydrocarbons. In Alberta and elsewhere in North America, the driving force towards inexpensive tests is the marginal economics of low deliverability wells. Either way, there is an increasing trend towards these green tests to replace conventional well tests. One such green test consists of simply allowing the well to flow into the closed wellbore after perforating (closed chamber test). As the fluid from the reservoir enters the wellbore (with a fixed volume), the wellbore pressure builds up. The pressure data is collected usually at the wellhead for a period of hours or days, depending on the reservoir's flow potential. These tests have been variously called: Slug test, Surge Test, Perforation Inflow Diagnostic (PID), or Closed Chamber Test. Interests in analyzing the data from this kind of tests have been documented in Reference 1.

Although, some efforts are reported in the literature to analyze the data from a perforation inflow test, none of these provides a complete set of reservoir information. In this study, we present a complete and systematic analysis procedure that yields estimates of initial reservoir pressure, permeability and skin. We have called this procedure "Perforation Inflow Test Analysis" (PITA). When the captured data is sufficient to see at least some portion of the reservoir-dominated flow, the resulting permeability and skin values can be determined uniquely. This means that in the case of small influx of fluid into the wellbore, one can determine if this is due to low permeability or high skin.

Mathematical Background

The basis of PITA is the slug-test model originally proposed by Ramey and co-workers[2, 3] in the seventies. A few years ago, Kuchuk[4] proposed a late-time approximation of the solution. Although the estimation of reservoir pressure with this approximate solution appears to be reasonable, the permeability estimation may not be. This can be appreciated by comparing the late-time solution of Kuchuk with the one for liquid to be presented later in this section (Equation 2).

As mentioned above, the solutions of PITA to be used in this study have been derived from the slug test formulation, as outlined by Ramey and co-workers in References 2 and 3. The following steps are involved in developing the working equations for analysis of data:

- Set up the diffusivity equation in pressure and time for liquid influx, and in pseudo-pressure and pseudo-time for gas influx, with appropriate initial and boundary conditions,
- Take Laplace transforms with respect to the temporal variable (time or pseudo-time) of the diffusivity equation and the boundary condition,
- Develop solution in the Laplace domain for pressure in liquid flow, or for pseudo-pressure in gas flow,
- Find the early- and late-time approximations of the solution in the Laplace domain,
- Invert analytically the early- and late-time approximations of the solution to the real time or pseudo-time domain. These early- and late-time approximations are indeed the straight-line solutions with appropriate plotting functions, which form the basis of PITA.

Details of the mathematical development are being presented in Reference 5. The early-time data is used to estimate skin, and the late-time data to estimate initial pressure and permeability. In gas wells, the pressure data is usually measured at the wellhead, and are converted to the bottom-hole condition. This conversion is primarily due to hydrostatic head, because the influx rate into the wellbore diminishes very rapidly, and frictional losses are not significant. Moreover, the analysis of gas well data requires the conversion of data – pressure to pseudo-pressure, and time to pseudo-time. The definitions and computational procedure of these pseudo-variables can be found in Reference 6. The fluid influx rate into the well is not measured, nor is it necessary for the analysis. Nevertheless, it can be estimated using closed chamber calculations, provided the assumption of single-phase flow can be justified. Figure 1 shows the typical profiles of measured pressure and calculated influx rate for a perforation test of a water well. As shown here, the influx rate declines very rapidly.

The working equations in practical metric units for liquid (single-phase oil or water) and gas cases are presented below:

Case I: Liquid Influx

Analysis of Early-Time Data

$$p_w = p_{w0} + \frac{kh\,(p_i - p_{w0})\,\Delta t}{(24)(1.842\times10^3)\mu\, C\, s} \quad \text{……………………..(1)}$$

Analysis of Late-Time Data

$$p_w = p_i + \frac{(24)(1.842\times10^3)\mu\, C\,(p_i - p_{w0})}{2kh\,\Delta t} \quad \text{…………….(2)}$$

Case II: Gas Influx

Analysis of Early-Time Data

$$\psi_w = \psi_{w0} + \frac{kh\,(\psi_i - \psi_{w0})\,\Delta t_a}{(24)(1.842\times10^3)V_w\, s} \quad \text{……………………..(3)}$$

Analysis of Late-Time Data

$$\psi_w = \psi_i + \frac{(24)(1.842\times 10^3) V_w\,(\psi_i - \psi_{w0})}{2kh\,\Delta t_a} \quad \ldots\ldots\ldots\ldots\ldots(4)$$

Influx Rate Calculations

Although calculations of influx rates are not required for analyzing the data for estimating reservoir properties, the influx rates can be calculated for any other diagnostic purposes by using the material balance principles as shown below:

Liquid Rate

$$q_l = \frac{(24)(1{,}000) V_u}{\rho g}\left(\frac{dp_w}{d\Delta t}\right) \quad \ldots\ldots\ldots\ldots\ldots(5)$$

Gas Rate

$$q_g = \frac{(24)\,V_w\,c_g}{(1{,}000)\,B_g}\left(\frac{dp_w}{d\Delta t}\right) \quad \ldots\ldots\ldots\ldots\ldots(6)$$

Flow Regimes

It is very obvious that the data for PITA is significantly influenced by wellbore storage. It is also very evident that the data is also directly influenced by the flow capacity (kh) and the skin. Therefore, one needs to distinguish the part of the data dominated by wellbore storage (afterflow effects) from the part of data that is dominated by reservoir characteristics (reservoir pressure and permeability). As shown in Equations 1 and 3, the early-time data contains information about the skin, because of significant fluid influx rates (see Figure 1). Also, Equations 2 and 4 show that the late-time data can be exploited to estimate reservoir pressure and permeability. Thus, proper identification of these flow regimes is important in order to choose appropriate data ranges from a perforation inflow test for appropriate analyses. Details of the analysis procedure are discussed in the next section.

From the authors' experience, it has been observed that the measured pressure in a set of data must contain at least some portion of the reservoir-dominated flow in order for the estimated reservoir pressure, permeability and skin to be representative of the reservoir. Alternatively speaking, the test period must be long enough to see the reservoir-dominated flow at late times. A special kind of derivative is used to confirm if the data has seen the reservoir-dominated flow. Cinco-Ley *et al*.[7] originally introduced this derivative, and later Kuchuk[4] called this "impulse derivative" (*IDER*), which can be defined as:

Liquid Influx

$$IDER = (\Delta t)^2 \frac{dp_w}{d\Delta t} \quad \ldots\ldots\ldots\ldots\ldots(7)$$

Gas Influx

$$IDER = (\Delta t_a)^2 \frac{d\psi_w}{d\Delta t_a} \quad \ldots\ldots\ldots\ldots\ldots(8)$$

This approach is similar to the traditional well-test interpretation, where a derivative plot is used to differentiate the wellbore flow regime from the infinite-acting radial flow regime. However, the derivative for PITA is different from the traditional derivative of well testing. Figure 2 shows the computed values of impulse derivative. Here, one can appreciate the advantage of using the impulse derivative, which behaves in a slightly different way from the traditional well-test derivative. As shown, the early-time data (wellbore storage) has a slope of 2 (well-test derivative has a slope of 1), and the late-time data (reservoir flow) has a slope of 0 (flat line – the same as the well-test derivative). This particular example shows that the test period should last for at least 160 hours for the estimated reservoir parameters to be representative.

Thus, once the impulse derivative has been plotted with time (or pseudo-time) in log-log scales, it is easy to recognize whether or not the reservoir-dominated flow exists. If it does, reasonable values of reservoir pressure, permeability and skin can be determined. At least some of the late-time data should fall on the flat part of the derivative as shown in Figure 2, in order to get a reliable analysis. If this data exists, then skin can be calculated from the early-time data. If there is no reservoir flow, then a unique interpretation of the given data is not possible.

Analysis of Data

In traditional well test interpretation, we start analyzing the data from early-time to late-time. In PITA, we start with the late-time data first, to obtain reservoir pressure and permeability. After this, we analyze the early-time data (where the derivative slope is 2) to obtain skin. Even though a complete analysis can be obtained from the derivative plot alone, it is useful to generate specialized plots to confirm the analysis. As presented earlier, the working equations for liquid and gas influxes are slightly different. For liquid influx, the data is analyzed in terms of pressure and time. For gas influx, the data is analyzed in terms of pseudo-pressure and pseudo-time. Table 1 summarizes the procedures for analyzing data for liquid and gas influxes, which involve specialized plots of derivative and bottom-hole pressures with different time scales. In liquid influx, we need to specify the wellbore storage constant (C) due to rising liquid level in the wellbore, which is a function of wellbore capacity (V_u) and liquid density. In gas influx, we need to specify the wellbore or chamber volume (V_w).

Now, we present two examples with synthetic data for water wells to illustrate the analysis technique discussed above. The analysis of data presented in Figures 1 and 2 are presented first as Example 1. The input parameters of Example 1 are shown in Table 2. As mentioned earlier, one needs to have data for at least 160 hours in order of estimate representative reservoir parameters. In the analysis, we are using this minimum amount of data. Figure 3 presents the analysis of the late portion of the data (for 160 hours). A straight line is drawn through the few last data points. The intercept of this straight line at $1/t = 0$ yields the reservoir pressure of 6,001 kPa (*cf.* model reservoir pressure of 6,000 kPa), and the slope yields a permeability of

0.8 mD (*cf.* model permeability of 1 mD). However, the permeability estimate can be improved to 0.98 mD if the data for 500 hours are available for this specific case. Figure 4 presents the analysis of the early-time portion of the same data set. A straight line is drawn anchoring at 4,000 kPa, which is the initial cushion pressure. Using the estimated reservoir pressure and permeability from the analysis of the late portion of the data, the slope of the line yields a skin of +5.86 (*cf.* model skin of +6). Example 1 indeed shows that the reasonable estimates of the reservoir parameters can be obtained with PITA.

The second synthetic set of data [Example 2] for a high-permeability reservoir is generated by using the parameters in Table 3. Figure 5 shows that one needs data for at least 20 hours for the analysis to be representative. Here, we are analyzing data for 20 hours to obtain the reservoir parameters. The late-time portion of the data is analyzed in Figure 6. The intercept of the straight line yields the reservoir pressure as 9,704 kPa (*cf.* model reservoir pressure of 9,700 kPa), and the slope yields the permeability as 95.8 mD (*cf.* model permeability of 110 mD). Figure 7 presents the analysis of the early portion of the data, anchoring at 6,200 kPa (the initial cushion pressure). Using the estimated initial reservoir pressure and permeability from the analysis of late-time data, the slope of the line yields a skin of +13.2 (*cf.* model skin of +12). Example 2 also shows that PITA is capable of yielding reasonable estimates of reservoir parameters.

An important question one may face, when observing a slow rate of pressure buildup in the wellbore, is whether the poor performance is because of high skin or low permeability. While the latter cause may lead to an abandonment of the well, the former may be resolved by stimulation. The two synthetic examples given above, show that PITA can differentiate between a case with high permeability and skin and another case with low permeability and skin. Moreover, the procedure to estimate the reservoir parameters with PITA is simple.

Discussion

It has been shown that PITA can yield reasonable estimates of the reservoir parameters, if the data contain some portion of the reservoir-dominated flow. This can be ascertained by computing the impulse derivative and plotting this with time (or pseudo-time) in log-log scales. If a given set of data contains some portion of reservoir-dominated flow, as demonstrated by a flat portion (zero slope) of the impulse derivative plot, the possibility of estimating a non-unique set of values of permeability and skin is reduced. This is because when the reservoir-dominated flow is not established, the reservoir pressure and permeability estimates will not be reasonable. Such poor estimates of reservoir pressure and permeability will adversely affect the estimate of skin (see Equation 1 and 3). Thus, when estimated properly, the reservoir parameters will reduce the chance of yielding a set of non-unique parameters significantly, when modeling the reservoir.

One significant advantage of PITA is that the analyst does not have to calculate the influx rates as part of the analysis of the data. Often, with a set of noisy pressure data, the calculated rate becomes noisier.

As shown earlier, wellbore volume or wellbore capacity needs to be known *a priori* for estimating the reservoir parameters. There can be occasions when these values may not be known with a reasonable accuracy. In such situations, an over-estimated wellbore volume or wellbore capacity will lead to an over-estimation of permeability (see Equations 2 and 4). However, the estimates of reservoir pressure and skin appear to be unaffected (see Equations 1 and 3), as a result of a poor estimate of the wellbore volume or wellbore capacity.

The development of the analysis procedure is well grounded in acceptable theory. As a result, we now have a much better sense of the interpretation and the validity of these very short tests, because we now have a clear understanding of the flow regimes. In practice, we know that the longer the flow, the better the test. Nonetheless, it is important to validate the results of PITA by comparing these with those from other tests – for example, permeability obtained from a traditional flow-buildup test, or reservoir pressure obtained from a static-gradient survey. Because of well cleanup and other such considerations, the value of skin could be different between various tests. Until we have enough experience to determine to what extent PITA can be relied on, we recommend that these comparisons be done as often as possible, and we encourage analysts to publish their results.

Conclusions

1. We have developed a systematic and comprehensive analysis of data obtained from perforation inflow tests.

2. Reasonable estimates of reservoir properties can be obtained, if the data sees at least some portion of the reservoir-dominated flow.

3. Impulse derivative should be used to confirm whether or not the pressure data contains any reservoir-dominated flow.

4. The late-time portion of data yields reservoir pressure and permeability, and the early-time portion yields the skin.

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NOMENCLATURE

B_g	=	Gas formation volume factor, m^3/m^3
c_g	=	Gas compressibility, kPa^{-1}
C	=	Wellbore storage constant for rising liquid level (oil or water), $1{,}000V_u / (\rho g)$, m^3/kPa
g	=	Acceleration due to gravity, 9.80665 m/s^2
h	=	Net pay thickness, m
k	=	Permeability, mD
IDER	=	Impulse derivative, defined in Equation 7, kPa-hr (liquid), and in Equation 8, $(kPa)^3$-hr/$(\mu Pa.s)^2$ (gas)
p_i	=	Initial reservoir pressure, kPa
p_w	=	Pressure at wellbore, kPa
p_{w0}	=	Initial cushion pressure or wellbore pressure at time $\Delta t = 0$, kPa
q_g	=	Rate of gas influx into wellbore, $10^3m^3/d$

q_l	=	Rate of liquid influx into wellbore, m^3/d
s	=	Skin factor
Δt	=	Time since beginning of fluid influx, hr
Δt_a	=	Pseudo-time since beginning of fluid influx, hr-kPa/μPa.s
V_u	=	Wellbore volume per unit length (wellbore capacity), m^3/m
V_w	=	Wellbore (chamber) volume, m^3
ψ_w	=	Pseudo-pressure at wellbore, $(kPa)^2/\mu Pa.s$
ψ_{w0}	=	Initial cushion pseudo-pressure or wellbore pseudo - pressure at time $\Delta t_a = 0$, $(kPa)^2/\mu Pa.s$
ψ_i	=	Initial reservoir pseudo - pressure, $kPa^2/\mu Pa.s$
ϕ	=	Porosity, fraction
μ	=	Liquid viscosity, mPa.s
ρ	=	Liquid density, kg/m^3

REFERENCES

1. HAWKWES, R.V., and DAKHLIA, H., Field Observations of Perforation Inflow Diagnostic (PID) Testing of Shallow Low-Permeability Gas Wells; *Paper 2004-282 presented at CIPC, Calgary, AB, June 8-10, 2004.*
2. RAMEY, H.J., JR., and AGARWAL, R.G., Annulus Unloading Rates as Influenced by Wellbore Storage and Skin Effect; *SPEJ, pp. 453-462, October 1972.*
3. RAMEY, H.J., JR., AGARWAL, R.G., and MARTIN, I., Analysis of 'Slug Test' or DST Flow Period Data; *Journal of Canadian Petroleum Technology, pp. 37-47, July-September 1975.*
4. KUCHUK, F.J., A New Method for Determination of Reservoir Pressure; *Paper SPE 56418 presented at SPE ATCE, Houston, TX, October 5-8, 1999.*
5. RAHMAN, N.M.A., POOLADI-DARVISH, M., and MATTAR, L., Development of Equations and Procedure for Perforation Inflow Test Analysis; *Paper SPE 95510 to be presented at SPE ATCE, Dallas, TX, October 9-12, 2005.*
6. RAHMAN, N.M.A., MATTAR, L., and ZAORAL, K., A New Method for Computing Pseudo-Time for Real Gas Flow Using the Material Balance Equation; *Paper 2004-182 presented at CIPC, Calgary, AB, June 8-10, 2004.*
7. CINCO-LEY, H., KUCHUK, F.J., AYOUB, J.A., SAMANIEGO-V., F. and AYESTARAN, L., Analysis of Pressure Tests through the Use of Instantaneous Source Response Concepts; *Paper SPE 15476 presented at SPE ATCE, New Orleans, LA, October 5-8, 1986.*

Type of Fluid Influx	Derivative Analysis	Late-Time Data Analysis	Early-Time Data Analysis
Water/Oil	• Basis: Equation 7 • Plot log [impulse derivative] versus log [time] for the entire data • Data on the zero-slope line represents the reservoir-dominated flow – use this to calculate p_i and k [*Late-Time Data Analysis*] • Data on the early-time line with slope 2 represents the afterflow-dominated flow – use this to calculate s [*Early-Time Data Analysis*]	• Basis: Equation 2 • Select an appropriate range of data from the Derivative Analysis • Plot p_w versus $1/\Delta t$ as a straight line • Estimate p_i from the intercept at $1/\Delta t = 0$ • Use slope of the line to estimate k	• Basis: Equation 1 • Select an appropriate range of data from the Derivative Analysis • Plot p_w versus Δt as a straight line with p_{w0} as an anchor point • Estimate s from the slope of the line, using the already estimated values of p_i and k.
Gas	• Basis: Equation 8 • Convert the raw data to pseudo-variables • Plot in log-log scales of the impulse derivative versus pseudo-time for the entire data • Data on the zero-slope line represents the reservoir-dominated flow – use this to calculate p_i (from ψ_i) and k [*Late-Time Data Analysis*] • Data on the early-time line with slope 2 represents the afterflow-dominated flow – use this to calculate s [*Early-Time Data Analysis*]	• Basis: Equation 4 • Select an appropriate range of data from the Derivative Analysis • Plot ψ_w versus $1/\Delta t_a$ as a straight line • Estimate ψ_i from the intercept at $1/\Delta t_a = 0$ • Convert ψ_i to p_i • Use slope of the line to estimate k	• Basis: Equation 3 • Select an appropriate range of data from the Derivative Analysis • Plot ψ_w versus Δt_a as a straight line with ψ_{w0} as an anchor point • Estimate s from the slope of the line, using the already estimated values of ψ_i and k.

TABLE 1: Summary of data-analysis procedures for liquid and gas influxes.

Permeability, k, mD	1
Initial reservoir pressure, p_i, kPa	6,000
Initial cushion pressure, p_{w0}, kPa	4,000
Total system compressibility, c_t, kPa^{-1}	4.5e-7
Viscosity, μ, mPa.s	0.553
Net pay thickness, h, m	10
Porosity, ϕ, fraction	0.2
Wellbore capacity, V_u, m^3/m	0.002
Skin, s	+6

TABLE 2: Input parameters to generate the synthetic data for Example 1.

Permeability, k, mD	110
Initial reservoir pressure, p_i, kPa	9,700
Initial cushion pressure, p_{w0}, kPa	6,200
Total system compressibility, c_t, kPa^{-1}	8.0e-7
Viscosity, μ, mPa.s	0.553
Net pay thickness, h, m	18
Porosity, ϕ, fraction	0.2
Wellbore capacity, V_u, m^3/m	0.026
Skin, s	+12

TABLE 3: Input parameters to generate the synthetic data for Example 2.

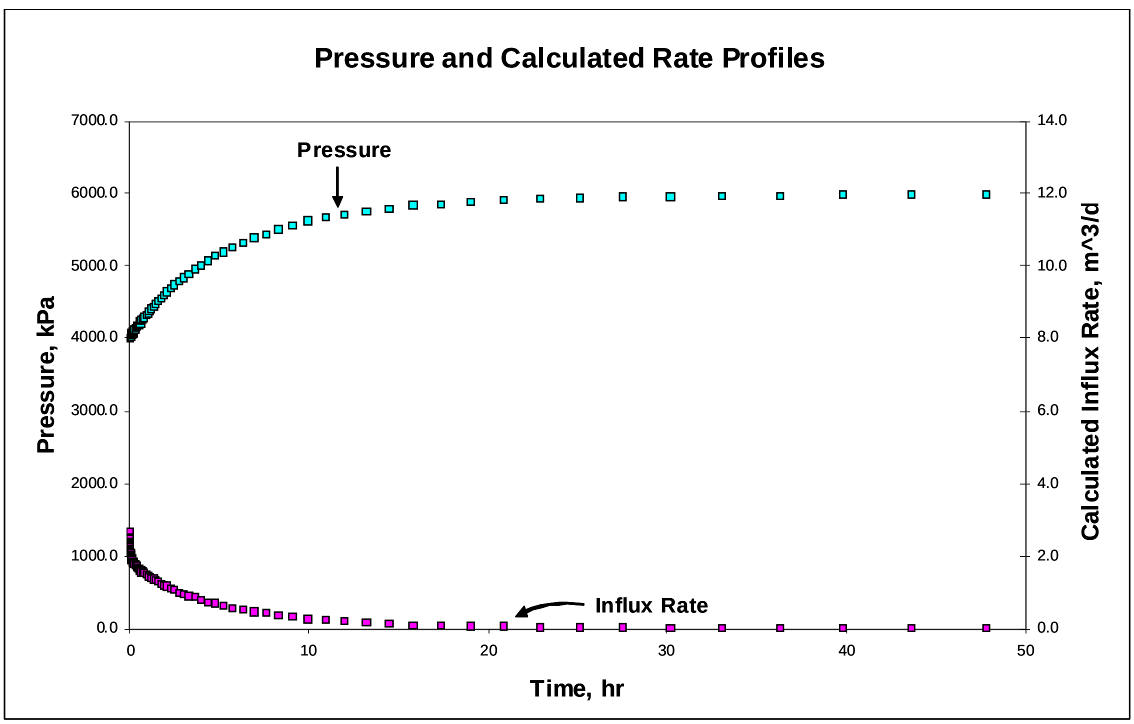

Figure 1: Typical pressure and calculated rate profiles in a perforation test.

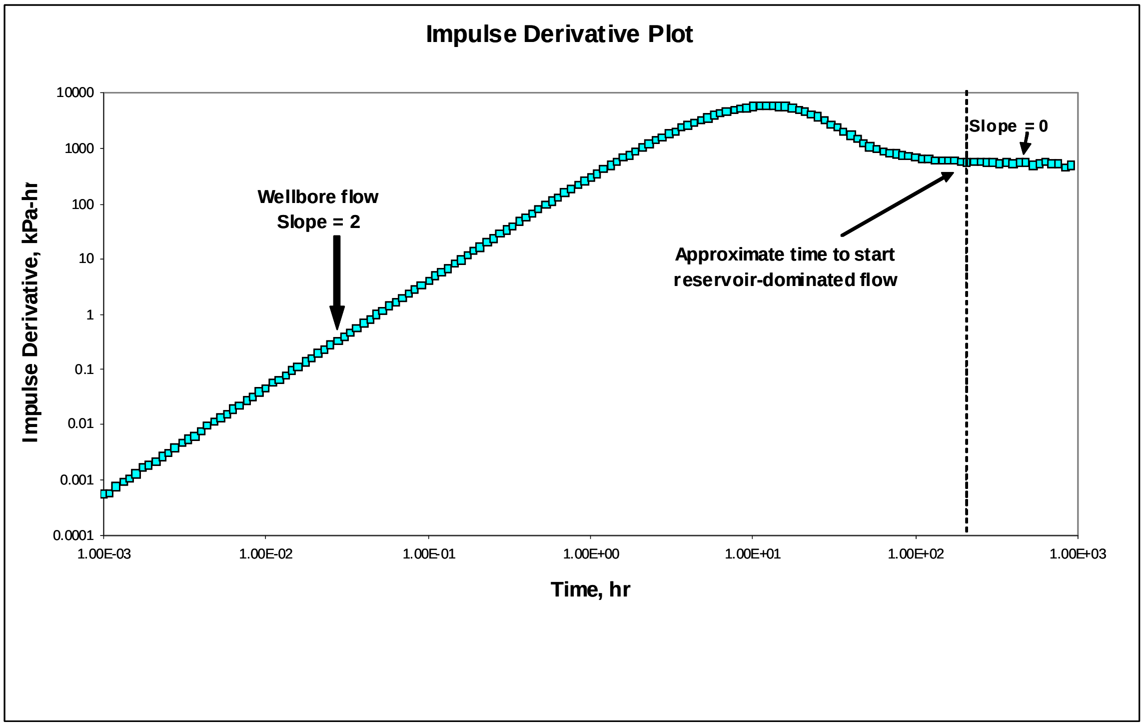

Figure 2: Impulse derivative contrasting the wellbore- and reservoir- dominated flow.

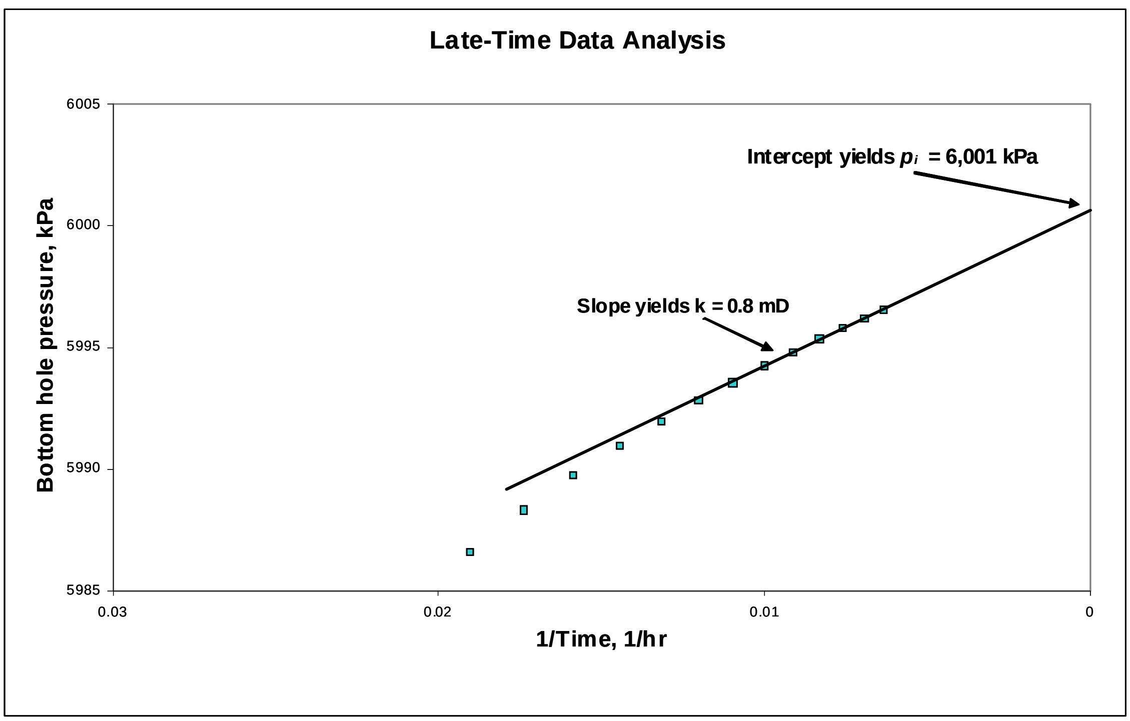

Figure 3: Late-time analysis for estimating reservoir pressure and permeability.

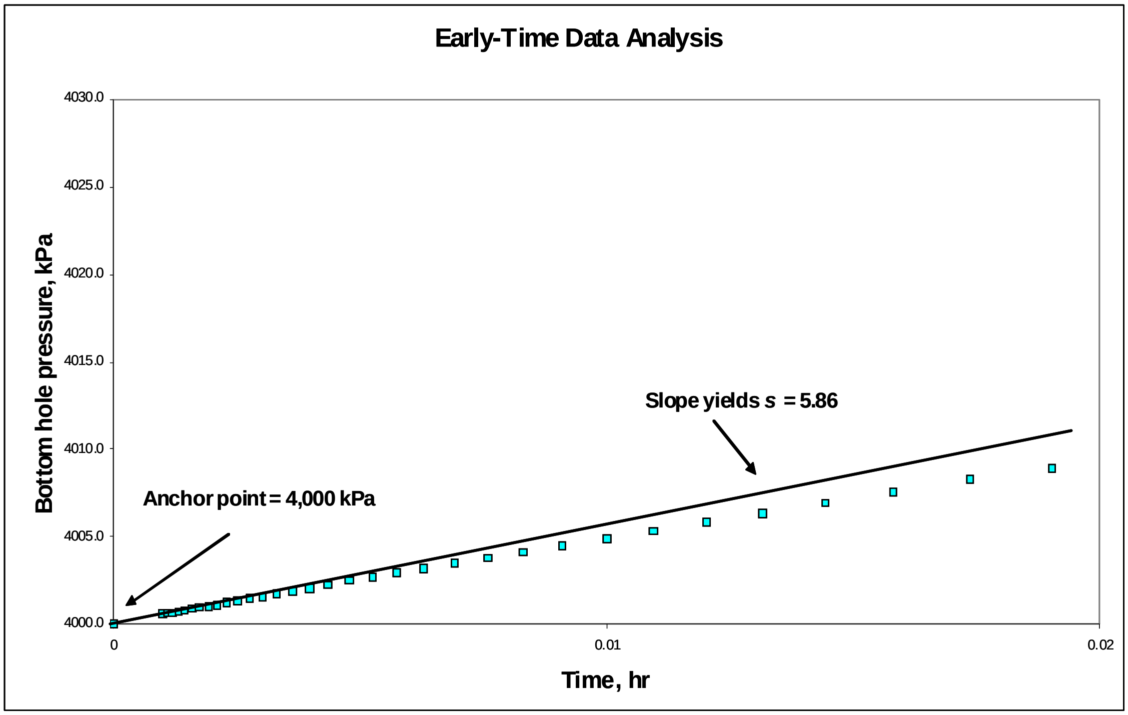

Figure 4: Early-time data analysis for estimating skin.

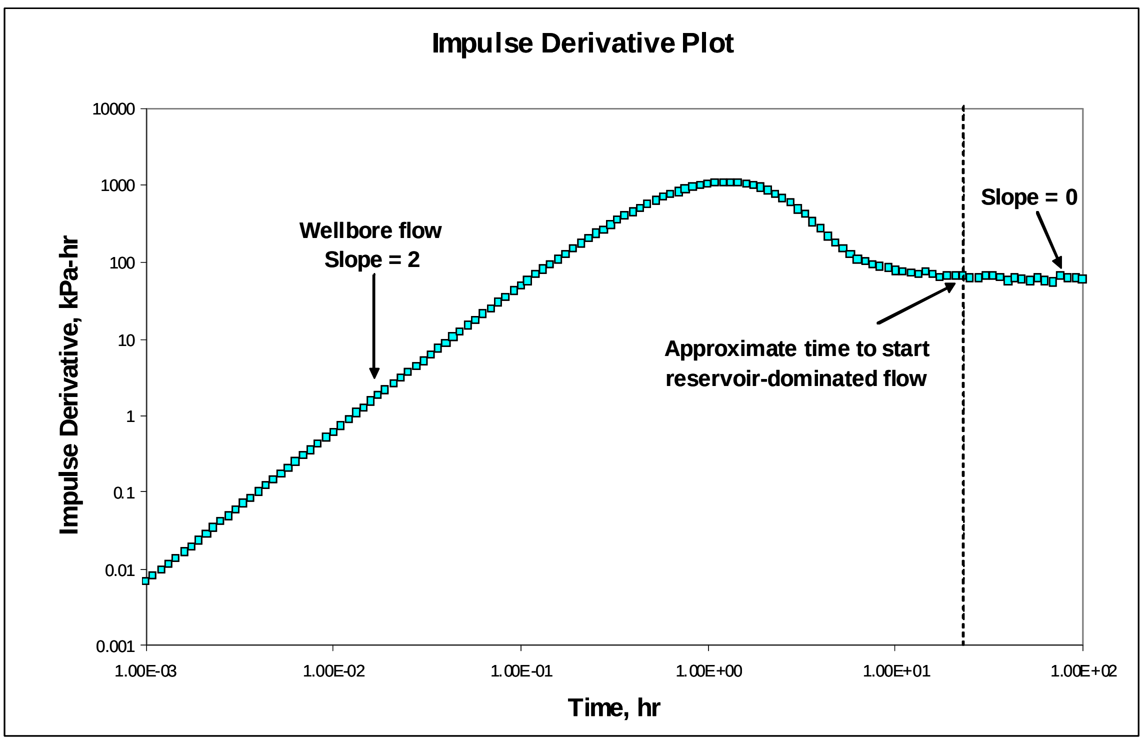

Figure 5: Impulse derivative for determining the onset of reservoir-dominated flow.

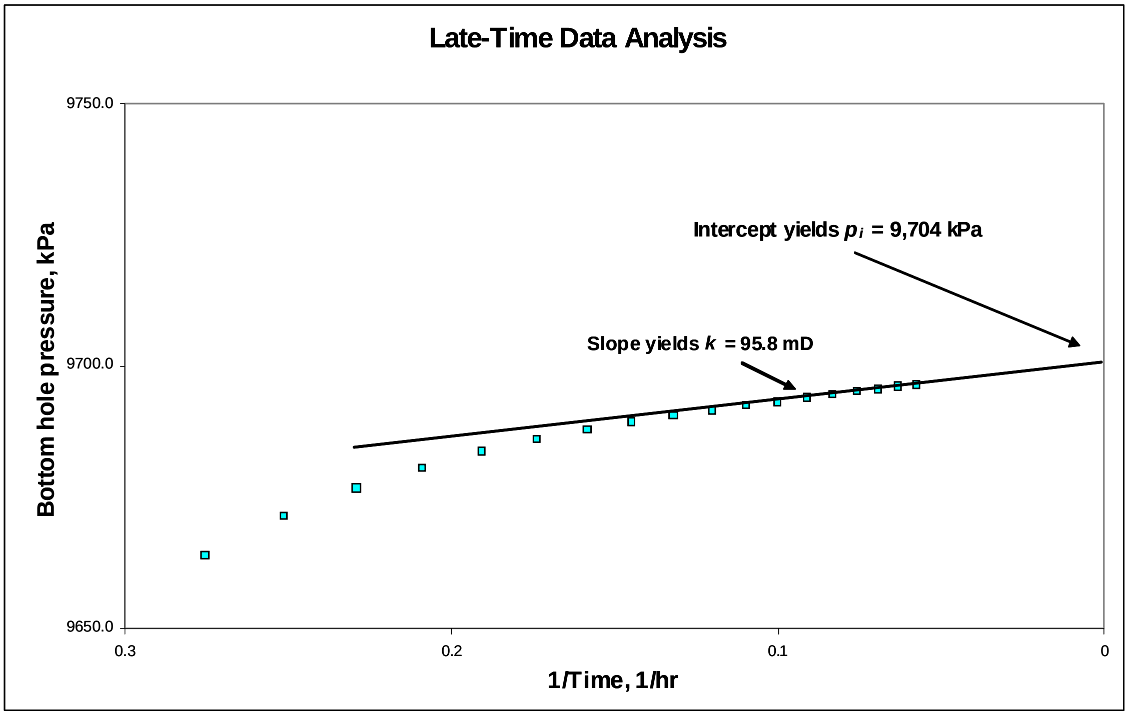

Figure 6: Late-time data analysis for estimating reservoir pressure and permeability.

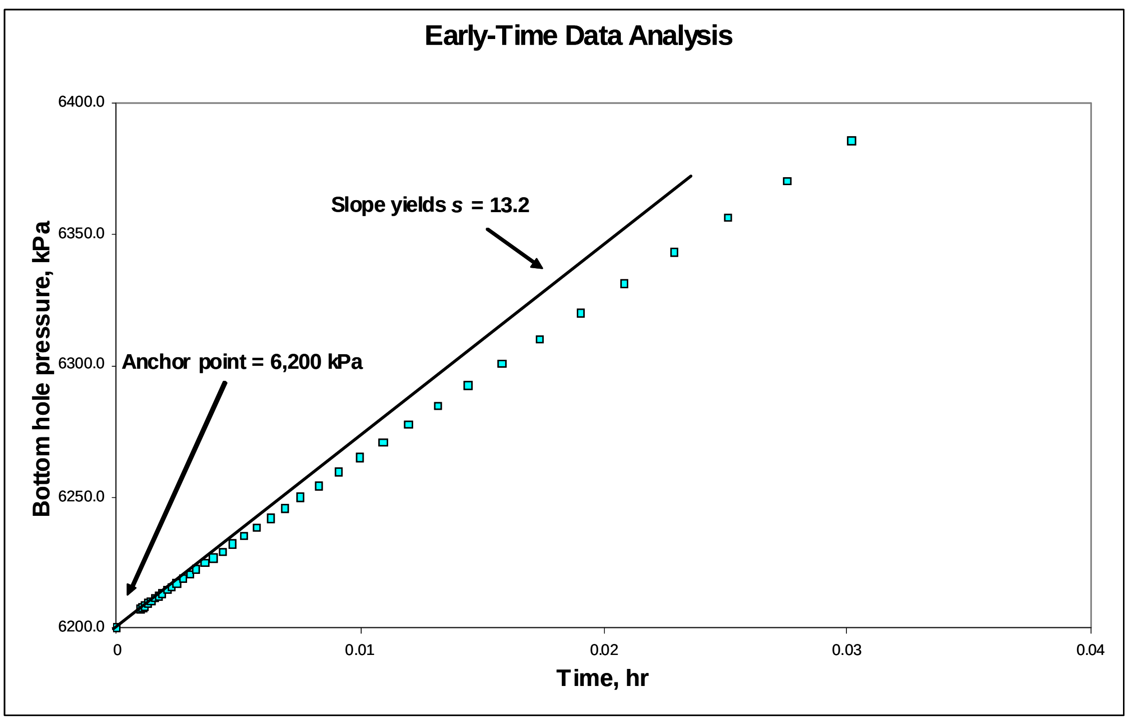

Figure 7: Early-time analysis for estimating skin.