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A METHOD FOR THE FLOW DIAGNOSIS AND INTERPRETATION OF A WELL TEST THROUGH THE USE OF THE PRESSURE DERIVATIVE FUNCTION

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ABSTRACT

This paper presents an alternative technique for transient pressure analysis. The new method is based on the pressure derivative function and the impulse theory. This method uses a mathematical and graphical evaluation of an equation of the type $[t_{corr,f}]\ t^{n_f}\Delta p_1' = m_f^1$, where n_f is related to the specific flow pattern toward the well and the constant m_f^1 with the formation conductivity. This procedure simultaneously allows the diagnosis of the flow pattern through the presence of a horizontal line of a graph of $[t_{corr,f}]\ t^{n_f}\Delta p_1'$ versus t, and an estimation of the formation conductivity through the value of the constant m_f^1, given by the intersection of this line with the ordinate axis. In the ordinate graphing group, $t_{corr,f}$ is a correction factor for variable rate producing conditions, approximately equal to unity for long producing times. For constant rate drawdown tests this factor is equal to one. f in this graphing group stands for the type of flow prevailing during a specific period of the test, i.e., spherical, linear, or radial. Variable well flow rates are also considered in the theory of analysis presented in this study. This new method is successfully applied to three field cases published in the literature.

INTRODUCTION

Forecasting reservoir perfomance requires complete information on reservoir definition and formation and fluid properties, among other things. Pressure transient testing when using an integrated approach, has proved to be a reliable method for the estimation of formation properties and characterization of several reservoir heterogeneities. Over the last five decades, hundreds of technical papers have been written on well test analysis (*Matthews and Russell* [1967];*Ramey et al.* [1973]; *Earlougher* [1977]; *Energy Resources Conservation Board* [1975]; *Streltsova* [1987]; *Horne* [1990];*Sabet* [1990]; *Stanislav and Kabir* [1990]; *Samaniego and Cinco* [1994]); this material includes solutions for transient flow problems, methods of analysis and practical aspects of testing procedures.

Different authors have addressed the question of a general approach to the analysis of a well test (*Gringarten* [1985];*Gringarten* [1987a]; *Ehlig-Economides* [1988]; *Cinco Ley and Samaniego* [1989]; *Ehlig-Economides et al.* [1990]; *Stanislav and Kabir* [1990]; *Horne* [1990]; *Ramey* [1992]; *Samaniego and Cinco Ley* [1994]). This approach consists of four main steps: 1) Estimation of the influence function or unit flow rate response through the deconvolution process; 2) Diagnosis of flow regime, ussually through the use of the pressure derivative function; 3) Application of specific graphs of analysis; 4) Non-Linear regression of the pressure data. It has been accepted that if this general methodology for the interpretation of a well test is used, following an integrated or synergy oriented approach, the goal of characterizing a reservoir system, and obtaining good estimates of its main parameters, can in most cases be achieved under favorable circumstances.

Recently *Jelmert* [1993a] and [1993b] has presented a methodology for flow diagnosis and type curve matching based on a polynomial derivative function. The main objective of this techique is to highlight both the slope and the intercept terms simultaneously. This is achieved by plotting the pressure data in the form of horizontal lines, which are easy to detect visually.

The purpose of this paper is to present an alternative technique for transient pressure analysis, which is based on the pressure derivative function and the impulse theory. This method uses a mathematical and graphical evaluation of an equation of the type $[t_{corr,f}]t^{n_f}\Delta p_1' = m_f^1$, where n_f^1 is related to the specific flow pattern toward the well and the constant m_f^1 with the formation conductivity. Thus, this procedure simultaneously allows the diagnosis of the flow pattern through the presence of a horizontal line in a log-log graph, and an estimation of the formation conductivity.

BASIC THEORY

The analysis of a transient pressure test is based in general, on a solution to a diffusivity type equation, that describes the flow of a specific fluid through a producing formation having constant porosity and permeability, which is given by Eq. 1:

$$k\nabla \cdot (\frac{\rho}{\mu}\nabla p) = \phi \rho c_t \frac{\partial p}{\partial t} \quad (1)$$

Eq. 1 may be expressed in an alternate way if the general pseudopressure $\psi(p)$ defined by Eq. 2 is used:

$$\psi(p) = \int_{p_o}^{p} \frac{\rho}{\mu} dp \quad (2)$$

Substituting Eq. 2 into Eq. 1:

$$k\nabla^2\psi(p) = \phi\mu c_t \frac{\partial \psi}{\partial t} \quad (3)$$

Eq. 3 is general in the sense that due to the nature of the definition of the pseudopressure ψ given by Eq. 2, the fluid considered can be either water or steam. In addition, it does not include the usual conventional diffusivity equation assumption of negligible square pressure gradients.

The diffusion type equation 3 can be written for the different flow regimes as follows:

$$(\frac{\partial^2 \Delta\psi}{\partial r^2} + \frac{\mathbf{n}}{r}\frac{\partial \Delta\psi}{\partial r}) = \frac{1}{\eta}\frac{\partial \Delta\psi}{\partial t} \quad (4)$$

where η is the hydraulic diffusivity and $\mathbf{n}$ refers to the flow geometry, with values of 0,1, and 2 for linear (L), radial (R) and spherical (S) flow, respectively; $\Delta\psi$ is the pseudopressure drop $\psi_i - \psi(r,t)$.

Solutions to Eq. 4 can be obtained considering an *instantaneous* extraction of a mass of fluid W, through a point, line or plane source, corresponding to the three different flow geometries already mentioned (*Carslaw and Jaeger* [1959]; *Gringarten and Ramey* [1973]; *Hantush and Jacob* [1955]):

a). Linear flow period:

$$\Delta\psi_{\text{ins},L}(r,t) = \frac{W}{\sqrt{k}\cdot A\ (4\pi\phi\mu c_t)^{1/2}}\frac{e^{-r^2/4\eta t}}{t^{1/2}} \quad (5)$$

b). Radial flow period:

$$\Delta\psi_{\text{ins},R}(r,t) = \frac{W}{4\pi\ k\cdot h}\frac{e^{-r^2/4\eta t}}{t} \quad (6)$$

c). Spherical flow period:

$$\Delta\psi_{\text{ins},E}(r,t) = \frac{(\phi\mu c_t)^{1/2}W}{8\pi^{3/2}\ k^{3/2}}\frac{e^{-r^2/4\eta t}}{t^{3/2}} \quad (7)$$

Solutions given by Eqs. 5-7 have been used in the analysis of impulse tests (*Ferris and Knowles* [1954]; *Cinco Ley et al.* [1986]; *Ayoub et al.* [1988]), where fluid extraction is carried out during a short time interval. It is important to notice that Eq. 6 includes the formation conductivity $k \cdot h$, while in Eq. 7 the permeability k appears raised to the 3/2 power, the units in both cases being the same L^3. Last, Eq. 5 for linear flow includes the product $\sqrt{k} \cdot A$ as a characteristic parameter, again with units L^3.

The influence function $\Delta\psi_1$ has been defined as a unit mass flow rate response (*Coats et al.* [1964]; *Cinco Ley et al.* [1986]), $\Delta\psi(r,t) = w\Delta\psi_1(r,t)$. Using this definition, the concept of an instantaneous source can be developed through the consideration of a continuous source during the time interval τ, of strength w, located at a point (x', y', z') (*Tijonov and Samarsky* [1983]). This source is equivalent to sources of strength $+w$ and $-w$, the first starting at $t = 0$ and the second at $t = \tau$. The pseudopressure distribution may be expressed:

$$\Delta\psi_\tau(r,t) = w[\Delta\psi_1(r,t) - \Delta\psi_1(r,t-\tau)] \quad (8)$$

During the time interval τ a total mass of fluid $W = w\tau$ is produced. Thus, Eq. 8 can be written:

$$\Delta\psi_\tau(r,t) = W[\frac{\Delta\psi_1(r,t) - \Delta\psi_1(r,t-\tau)}{\tau}] \quad (9)$$

Taking limits for $\tau \to 0$, considering a constant w, we obtain:

$$\lim_{\tau \to 0} \Delta\psi_\tau(r,t) = \Delta\psi_{ins}(r,t) = W\frac{\partial\Delta\psi_1(r,t)}{\partial t} \quad (10)$$

An alternate form to Eq. 10 is as follows:

$$\Delta\psi_{ins\ 1} = \frac{\Delta\psi_{ins}(r,t)}{W} = \frac{\partial\Delta\psi_1(r,t)}{\partial t} \quad (11)$$

In general, for a variable rate flow test, the pseudopressure drop $\Delta\psi(t)$ can be written:

$$\Delta\psi(t) = \sum_{i=1}^{N}(w_i - w_{i-1})\Delta\psi_1(t - t_{i-1}) \quad (12)$$

Taking the derivative of this expression and using Eq. 11:

$$\frac{\partial\Delta\psi(t)}{\partial t} = \sum_{i=1}^{N}(w_i - w_{i-1})\frac{\partial\Delta\psi_1(t-t_{i-1})}{\partial t}$$
$$= \sum_{i=1}^{N}(w_i - w_{i-1})\psi_{ins\ 1}(t - t_{i-1}) \quad (13)$$

For flow diagnosis and interpretation purposes, using Eq. 11, Eqs. 5-7 can be expressed in general form, for the producing well $r = 0$, as follows:

$$t^{n_f}\frac{\partial\Delta\psi_1}{\partial t} = m_f \quad (14)$$

where the expressions for the slope m_f and the values of the exponent n_f, for the three flows regimes corresponding to Eqs. 5-7, are presented in Table 1.

TABLE 1. EXPRESSION FOR THE SLOPE m_f AND THE EXPONENT n_f FOR LINEAR, RADIAL AND SPHERICAL FLOW.

Type of Flow	n_f	m_f
Linear (L)	$\frac{1}{2}$	$1/\sqrt{k} \cdot A\ (4\pi\phi\mu c_t)^{1/2}$
Radial (R)	1	$1/4\pi\ k \cdot h$
Spherical (S)	$\frac{3}{2}$	$(\phi\mu c_t)^{1/2}/8\pi^{3/2}k^{3/2}$

For variable flow rate conditions, using Eq. 11 and Eqs. 5-7, Eq. 13 can be written:

$$[t_{corr,f}]\ t^{n_f}\frac{\partial\Delta\psi_1(t)}{\partial t} = [t_{corr,f}]\ t^{n_f}\Delta\psi_1'(t) = m_f \quad (15)$$

where $t_{corr,f}$ is a correction time for variable rate producing conditions,

$$t_{corr,f} = [\frac{w_1}{w_N} + \frac{1}{w_N}\sum_{i=2}^{N}(w_i - w_{i-1})\frac{t^{n_f}}{(t-t_{i-1})^{n_f}}]^{-1} \quad (16)$$

and the influence function $\Delta\psi_1$ is equal to $\Delta\psi/w_N$.

For radial flow, two particular cases of the correction time $t_{corr,f}$ deserve discussion. First, a constante rate drawdown test, $w_1 = w_2 = \ldots = w_N$, results in $t_{corr,R} = 1$. Second, a buildup test after constant rate producing conditions gives $t_{corr,f}$ expressed by Eq. 17:

$$t_{corr,R} = \frac{(t_p + \Delta t)}{\Delta t} \tag{17}$$

with t^{n_f} in Eq. 15 being Δt^{n_f}.

For linear and spherical flow conditions, constant rate buildup tests result in the following expressions for $t_{corr,f}$:

$$t_{corr,L} = \frac{(t_p + \Delta t)^{1/2}}{(t_p + \Delta t)^{1/2} - \Delta t^{1/2}} \tag{18}$$

$$t_{corr,S} = \frac{(t_p + \Delta t)^{3/2}}{(t_p + \Delta t)^{3/2} - \Delta t^{3/2}} \tag{19}$$

Eq. 15 suggest that if for a fixed value of the exponent n_f a horizontal line in a log-log paper, of at least 3/4 of a cycle, is defined, we would be able to diagnostic the flow pattern prevailing during the test, allowing through the value of the constant ordinate of this line and the particular expression for m_f (Table 1), the estimation of the permeability related parameter, $\sqrt{k} \cdot A$, $k \cdot h$ or $k^{3/2}$, for linear, radial or spherical flow, respectively.

To evaluate the influence function derivative $\Delta\psi_1'$ that appears in Eq. 15, the following expression based on the chain rule of differentiation and Eq. 2 can be used:

$$\frac{\partial \Delta\psi}{\partial t} = \frac{\rho}{\mu}\frac{\partial \Delta p}{\partial t} \tag{20}$$

where the pressure drop Δp is defined by $p_i - p$.

If the phase flowing through the formation is liquid water, substituting Eq. 20 in Eq. 15 results:

$$[t_{corr,f}]t^{n_f}\Delta p_1' = m_f^1 \tag{21}$$

where the constant α_w is equal to $1E6$ for pressure expressed in MPa, the influence function Δp_1 is defined by $\Delta p/w_N$, and m_f^1 for water flow conditions is given by:

$$m_f^1 = \frac{\mu}{\alpha_w \rho} m_f \tag{22}$$

It has been assumed that average values for the viscosity and density within the pressure interval of interest can be assigned.

For steam flowing through the formation similarly, using the general gas law for real gases (*Katz et al.* [1959], Eq. 15 can be expressed:

$$[t_{corr,f}]t^{n_f}(\Delta p_1^2)' = m_f^1 \tag{23}$$

where $\Delta p_1^2 = (p_i^2 - p^2)/w_N$ and the constant α_s is iqual to $1E12$ for pressure expressed in MPa, and m_f^1 for steam flow conditions is given by:

$$m_f^1 = \frac{2\mu ZRT}{\alpha_s M} m_f \tag{24}$$

A similar average values assumption to that just made for the case of water has to be taken with regard to viscosity and the compressibility factor Z.

There are some physical conditions present in geothermal reservoirs where the previous assumption of average property values does not strictly apply, among them the case of a water with high dissolved solids content and of steam with a high non-condensible gases percentage. In these cases it is preferable to evaluate the pseudopressure defined by Eq. 2 following the procedure suggested by *Al-Hussainy, Ramey and Crawford* [1966].

EXAMPLES OF APLICATION

In this section the proposed technique of analysis presented in this paper is applied to three field tests. Previous to the analysis, the pressure data were properly smoothed.

Example A. This example corresponds to a buildup test carried out in a water producing well H-16 of the Los Humeros geothermal field, Mexico. The data for this test is shown in Table 2. The diagnostic graph for this example, and examples B y C to follow, is constructed by means of Eqs. 21 and 23, with $t_{corr,f}$ given by Eqs. 17 and 18, and it is shown in Fig. 1. It can be observed that the pressure behavior follows a horizontal line for radial flow conditions, for approximately one log cycle. The values of the ordinate m_R^1 is $0.045 MPa\ kg/s$.

Thus, the estimate for the formation conductivity through the right hand side of Eq. 21, also given by Eq. 22, and Table 1 is as follows.

$$
\begin{aligned}
kh &= \frac{\mu}{\alpha_w \rho \; 4\pi m_R^1} \\
&= \frac{9.08E{-}5}{(1E6)(695)(4\pi)(0.045)} \\
&= 2.31E{-}13m^3
\end{aligned}
$$

TABLE 2. PRESSURE DATA FOR THE BUILDUP TEST IN WELL H-16

Production rate, w, kg/s	11
Production time, t_p, h	2736
Temperature, T, $°C$	315
Water density, ρ, kg/m^3	695
Water viscosity, μ, $Pa\ s$	$9.08E{-}5$

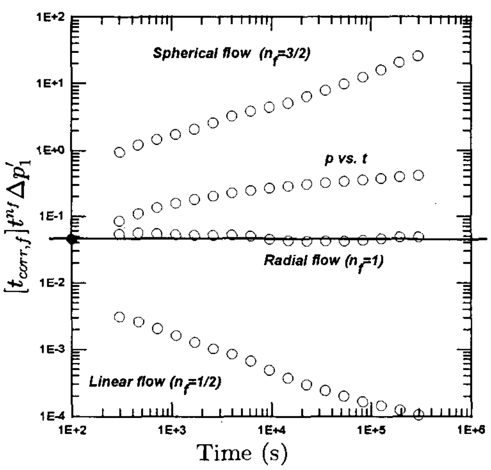

Figure 1: Diagnostic graph for Well H-16.

Example B. A pressure buildup test in a steam producing well Az-17 of Los Azufres geothermal reservoir, México (*S. Upton and Horne* [1989]), is analyzed. Data for this test are presented in Table 3, below. The diagnosis graph is shown in Fig 2. It can be noticed that the pressure bahavior follows a horizontal line for linear flow conditions, for approximately two log cycles. This finding is very much geologically supported by the fault Puentecillas, which is intersected by this well. The value of the ordinate m_L^1 is 0.0007 $s^{1/2}MPa^2$ kg/s. Thus, the estimate for the product $\sqrt{k}\cdot A$ through the right hand side of Eq. 23, also given by Eq. 24, and table 1 is as follows:

$$
\begin{aligned}
\sqrt{k}\cdot A &= \frac{2\mu ZRT}{\alpha_s M(4\pi\phi\mu c_t)^{1/2} m_L^1} \\
&= \frac{2(1.8E{-}5)(1)(8314.3)(537)}{1E12(18.016)(2.83E{-}12)^{1/2}(0.0007)} \\
&= 7.58E{-}3m^3
\end{aligned}
$$

TABLE 3. PRESSURE DATA FOR THE BUILDUP TEST IN WELL AZ-17

Production rate, w, kg/s	9.81
Production time, t_p, h	144
Temperature, T, $°K$	537
Steam viscosity, μ, $Pa\ s$	$1.8E-5$
Compressibility, c_t, Pa^{-1}	$0.2495E-6$
Porosity, ϕ,	0.05

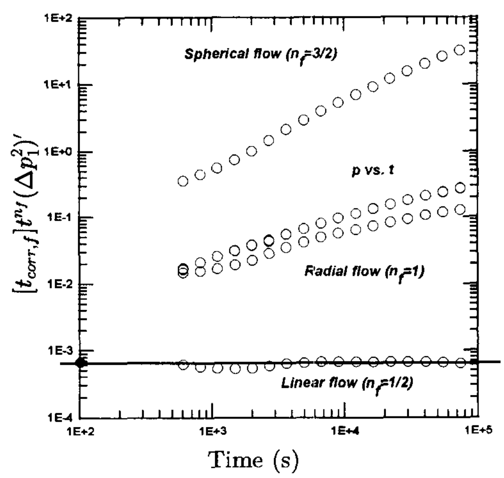

Figure 2: Diagnostic graph for Well AZ-17.

Example C. This is a drawdown test in a steam well reported by *Economides et al.* [1982]. The basic data are presented in Table 4. The diagnosis graph is shown in Fig. 3, observing that the pressure behavior follows a horizontal line for radial flow conditions, for approximately three quarters of a log cycle.

The ordinate m_R^1 is $0.0425s^{1/2}MPa$ kg/s. The formation conductivity $k\cdot h$ can be estimated through the right hand side of Eq. 23, also expressed by Eq. 24, and Table 1:

$$
\begin{aligned}
kh &= \frac{2\mu ZRT}{\alpha_s 4\pi M m_R^1} \\
&= \frac{2(1.7E-5)(0.84)(8314.3)(513)}{(1E12)(4\pi)(18.016)(0.0425)} \\
&= 1.26E{-}11m^3 = 4.2E4md-ft.
\end{aligned}
$$

This estimation for the conductivity compares very well with the reported value by Economides et al. of $4.26E4md-ft$.

TABLE 4. PRESSURE DATA FOR THE DRAWDOWN TEST IN EXAMPLE C

Production rate, w, kg/s	21
Temperature, T, $°K$	513
Steam viscosity, μ, Pas	$1.7E-5$
Compressibility Factor, Z	0.84

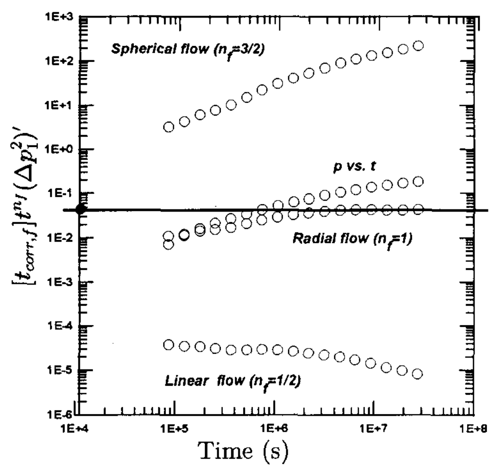

Figure 3: Diagnostic graph for example C.

CONCLUSIONS

The principal purpose of this paper has been to present an alternative technique for transient pressure analysis, which is based on the pressure derivative function and the impulse theory.

The main conclusions of this work are as follows:

1. This method is based on a mathematical and graphical evaluation of an equation of the type $[t_{corr,f}]\,t^{n_f}\Delta p_1' = m_f^1$, where n_f is related to the specific flow pattern towards the well and the constant m_f^1 with the formation conductivity.
2. This procedure simultaneously allows the diagnosis of the flow pattern through the presence of a horizontal line in a log-log graph, and an estimation of the formation conductivity.
3. The type of flow tests considered in this technique are drawdown and buildup tests, for both constant and variable rate conditions.
4. The different flow patterns analized are linear, spherical and radial.
5. This method was successfully applied to three field cases.

NOMENCLATURE

A = Area for linear flow, m.

c_t = Total system compressibility, Pa^{-1}.

h = Formation thickness, m.

k = Formation permeability, m^2.

$k \cdot h$ = Formation conductivity, m^3.

$\sqrt{k} \cdot A$ = Product of the square root of permeability and the area perpendicular for linear flow, m^3.

m_f^1 = Slope of the pseudopressure behavior graph, Eq. 15.

M = Molecular weight, $kg/kmol$.

n_f = Parameter that refers to the flow geometry, Table 1 and Eq. 21.

N = Number of different flow rates for a fixed time t.

p = Pressure, Pa.

p_i = Initial pressure, Pa.

Δp_1 = Influence function, Eq. 21.

r = Distance from the producing point, m.

R = Gas constant, 8314.3 $J/kmol\ °K$.

r_w = Wellbore radius, m.

$t =$ Time, s.

$t_p =$ Producing time, s.

$\Delta t =$ Shut-in time, s.

$w =$ Mass flow rate, kg/s.

$W =$ Instantaneous fluid mass extraction, kg.

$\Delta =$ Difference.

$\alpha_s =$ Unit conversion constant for steam flow for pressure expressed in MPa, $1E12$, Eq. 23.

$\alpha_w =$ Unit conversion constant for water flow for pressure expressed in MPa, $1E6$, Eq. 21.

$\mu =$ Viscosity, $Pa\ s$.

$\eta =$ hydraulic diffusivity, $k/\phi\mu c_t$, m^2/s.

$\rho =$ Density, kg/m^3.

$\phi =$ Porosity, (fraction).

$\tau =$ Time interval, Eq. 8.

$\psi(r,t) =$ Pseudopressure, Eq. 2, kg/m^3s.

$\Delta\psi(r,t) =$ Pseudopressure change, $\psi_i - \psi(r,t)$.

$\Delta\psi_1(r,t) =$ Influence Function, Eq. 8.

$\Delta\psi_{ins\ 1}(r,t) =$ Derivative with respect to time of the influence Function, Eq. 11.

$\nabla\cdot =$ Divergence operator.

$\nabla^2 =$ Laplacian operator.

Subscripts

$o =$ reference, Eq. 2

$1 =$ influence function

$f =$ phase

$i =$ initial or index

$ins =$ instantaneous

L= linear, Eq. 5

R= radial, Eq. 6

S= spherical, Eq. 7

Superscripts

$'$ first derivative.

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