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Estimation of Hydrocarbon-Pore Volumes in Compartmentalized Systems Using the Concept of Pseudosteady State

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Abstract

An estimation of hydrocarbon-pore volumes is a very important step forward in estimating hydrocarbon reserves. However, this process becomes very complicated when a hydrocarbon reservoir is compartmentalized. In this study it has been shown that the use of the concept of pseudosteady state can be exploited to estimate the hydrocarbon-pore volume in each compartment of a compartmentalized reservoir. Drawdown responses at the wellbore are considered to ensure that a pseudosteady state has been reached in compartments.

Nomenclature

A_i	Dimensionless area of *ith* compartment, area/X_p^2
c_t	Total compressibility of producing compartment, Pa^{-1}
$c_{t\,i}$	Total compressibility of *ith* compartment, Pa^{-1}
e_i	$(B_p\, \phi_i\, c_{t\,i}\, h_i)/ (B_i\, \phi_p\, c_{t\,p}\, h_p)$
h_i	Pay thickness in *ith* compartment, m
h_p	Reference pay thickness, m
$h_{p\,D}$	h_p/X_p
k_i	Permeability in *ith* compartment
N_p	Hydrocarbon-pore volume per unit drawdown pressure, defined in Eqs. (3) and (12), sm^3/Pa
$N_{p\,1}$, $N_{p\,2}$	Hydrocarbon-pore volume per unit drawdown pressure in compartments 1 and 2, defined in Eqs. (8) and (9), respectively, sm^3/Pa
p_o	Initial pressure, Pa
p_w	Wellbore pressure, Pa
p_w'	Cartesian derivative of wellbore pressure with respect to time, Pa/s
$p_{w\,D}$	Dimensionless wellbore pressure, $(k_p\, h_p/q_p\, \mu_p\, B_p)\,(p_o - p_w)$
p_{wD}'	Cartesian derivative of dimensionless wellbore pressure with respect to dimensionless time
q	Constant rate of production, sm^3/s
q_D	q/q_p
t	Elapsed time, s
t_D	$k_p\, t/(\phi_i\, \mu_p\, c_{t\,p}\, X_p^2)$
V	Volume of producing compartment, m^3
V_i	Volume of *ith* compartment, m^3
X_{0D}	X_0/X_p
Y_{0D}	Y_0/X_p
X_p	Reference length, m

ϕ Porosity of producing compartment
ϕ_i Porosity of *ith* compartment
μ Viscosity of fluid in producing compartment, Pa.s
μ_i Viscosity of fluid in *ith* compartment, Pa.s

Subscripts

i *ith* compartment
p Reference compartment or parameter

Introduction

A compartmentalized reservoir is made up of a number of hydraulically communicating regions or compartments. The communication between a pair of adjoining compartments may be poor due to the presence of faults or low-permeability barriers [1]. A number of compartmentalized reservoirs have been discovered around the world including those in the North Sea [2], Texas Gulf Coast [3-5], Australia [6], and South East Asia [7]. Evidence of reservoir compartmentalization has been observed in both oil and gas reservoirs [5]. Reservoir compartmentalization is detected primarily from the observation of discontinuities in pressure, both with areal and vertical extents that have been found in producing fields while running wireline formation tester surveys in newly drilled wells [8].

It is important to estimate the hydrocarbon-pore volumes of individual compartments for the purpose of estimating the reserves. Such an effort gets complicated due to the presence of compartmentalization. During a period of pseudosteady state, the pressure at every point in the flow domain of a reservoir declines due to the production at a constant rate. Applying this concept, the hydrocarbon-pore volumes of individual compartments can be estimated. No previous, systematic attempts to compute the hydrocarbon-pore volumes capitalizing on the pseudosteady state have been reported in the literature. Here, two compartmentalized systems will be considered to illustrate the idea.

Extended Drawdown Analysis

(i) A Small Compartment in Communication with a Big one

In this section, one of the very important aspects of reservoir compartmentalization will be considered. Sometimes, it is discovered that a small compartment is in hydraulic communication poorly with a big one [2]. Here the volume and hydraulic diffusivity of the supporting compartment are considered very large in comparison to those in the producing compartment. Any extra resistance to flow for poor communication of fluid between the compartments is measured by the skin factor. The big compartment has been termed "source reservoir" by *Fox et al.* [2]. According to *Stewart* and *Whaballa* [8], because of its large size, the depletion of the supporting compartment is very slow indeed and it remains essentially at the initial pressure. Therefore, any production from the small compartment apparently would not have any effect on the pressure behavior of the neighboring big compartment in the short term. It is apparently a situation where the condition at the extreme boundary (at the interface on the side of the big compartment) can be considered as a constant-pressure one. As a result of such consideration, the condition at the communicating boundary is, indeed, a Cauchy-type one [9,10]. This situation is illustrated schematically in Figure 1. However, in this section, the small compartment is considered to be producing through a well, located at the center, at a constant rate of $q_D = 1$. The region within the small compartment with a well, bounded by the sides $0 \le x_D \le X_{0\,D}$ and $0 \le y_D \le Y_{0\,D}$ in areal extent, has a dimensionless pay thickness of h_D. Here, it is also considered that $X_{0\,D} = Y_{0\,D} = h_D = 1$.

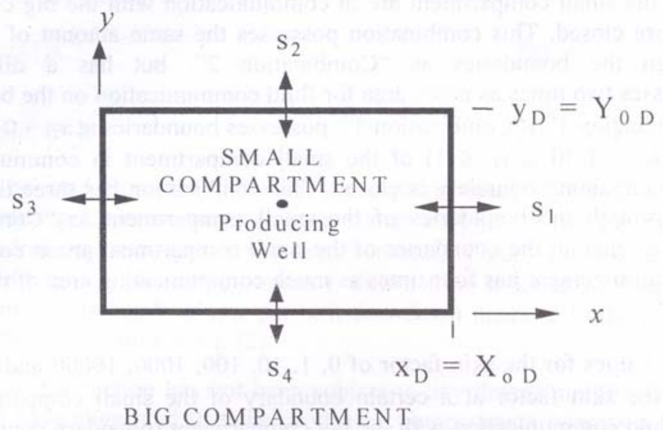

Fig.1. A schematic showing a small compartment in communication with a big one.

Table 1 identifies all the boundaries in terms of location, extent and specification with a skin factor. There is a possibility that not all of the boundaries of the small compartment may be in complete communication with the big compartment. Hence, all possible combinations of the conditions at the boundaries of the small compartment need to be analyzed. These combinations of the values of the skin factor on the boundaries to be considered are shown in Table 2.

Table 1: Location, extent and specification of skin factor of communicating boundaries.

Location	Extent	Skin Factor
$x_D = 1$	$0 \le y_D \le 1$	S_1
$y_D = 1$	$0 \le x_D \le 1$	S_2
$x_D = 0$	$0 \le y_D \le 1$	S_3
$y_D = 0$	$0 \le x_D \le 1$	S_4

Table 2: Combinations of skin factors at the boundaries of a small compartment.

Combination	S_1	S_2	S_3	S_4
1	Finite	∞	∞	∞
2	Finite	Finite	∞	∞
3	Finite	∞	Finite	∞
4	Finite	Finite	Finite	∞
5	Finite	Finite	Finite	Finite

"Combination 1", for example, refers to a condition where the boundary at $x_D = 1$ $(0 \le y_D \le 1)$ of the small compartment is considered to be in communication with the big compartment while all the remaining boundaries are closed. Similarly, with "Combination 2", there are boundaries at $x_D = 1$ $(0 \le y_D \le 1)$ and at $y_D = 1$ $(0 \le x_D \le 1)$ of the small compartment in communication with the big compartment while the remaining boundaries are closed. With "Combination 3", the boundaries located at $x_D = 0$ $(0 \le y_D \le 1)$ and

$x_D = 1$ ($0 \leq y_D \leq 1$) of the small compartment are in communication with the big compartment while the remaining boundaries are closed. This combination possesses the same amount of surface area for fluid communication through the boundaries as "Combination 2", but has a different configuration. "Combination 3" possesses two times as much area for fluid communication on the boundaries of the small compartment as "Combination 1". "Combination 4" possesses boundaries at $x_D = 0$ ($0 \leq y_D \leq 1$), at $y_D = 1$ ($0 \leq x_D \leq 1$), and at $x_D = 1$ ($0 \leq y_D \leq 1$) of the small compartment in communication with the big compartment while the remaining boundary is closed. This combination has three times as much area for fluid communication through the boundaries of the small compartment as "Combination 1". Finally, "Combination 5" assumes that all the boundaries of the small compartment are in communication with the big compartment. This arrangement has four times as much communicating area of the small compartment as in "Combination 1".

For each boundary, the values for the skin factor of 0, 1, 10, 100, 1000, 10000 and ∞ are considered. An infinite value (∞) for the skin factor at a certain boundary of the small compartment means that the boundary is closed to fluid communication with the big compartment (boundary condition of the Neumann type). Similarly, a zero value for the skin factor means that the boundary on the side of the small compartment is maintained at a constant pressure with the big compartment (boundary condition of the Dirichlet type). Thus, the small compartment would tend to be closed for fluid communication altogether as the value of the skin factor at all boundaries tends to have a limiting value of infinity (∞). However, zero and infinite values for the skin factor are meant to consider the respective extreme situations that are possible as far as a boundary condition is concerned.

All the reference parameters regarding the reservoir geometry, and the rock and fluid properties, are taken with respect to the small compartment. Initially, the whole reservoir is considered to be at a constant, uniform pressure. In the definition of dimensionless pressure, the initial pressure of the reservoir is taken as the reference pressure, p_p. Therefore, the dimensionless initial pressure everywhere in the reservoir is zero and $p_{wD}(a_D, b_D, 0) = 0$. The analytical solutions of *Rahman* and *Ambastha* [11] are used for analysis in this study.

Reference [10] has demonstrated the dimensionless pressure responses in drawdown at the wellbore for different values of the skin factor at the communicating boundary for "Combination 1" through "Combination 5". The infinite-acting, radial-flow periods at early times are characterized by the line (up to about $t_D = 0.1$) before the effects of the boundaries are felt. However, the boundary-dominated flow regimes are characterized by the respective value of the skin factor. At late times, such a system leads to a steady state unless the entire boundary is a non-communicating one. It has also been shown in Reference [11] that there is a time period, between the end to the infinite-acting, radial-flow period and the start of the steady-state flow period, at which the system undergoes a pseudosteady state. This period of pseudosteady state depends on the combination of boundaries and the value of the skin factor. In other words, the producing compartment behaves as if its boundaries are all no-flow type for some time before the system reaches a steady state. However, such an observation is consistent with those found in References [12,13].

At late times, the flow leads to the steady state, regardless of any finite value of the skin factor. The dimensionless time required to reach the steady state is longer for higher values of the skin factor, in any combination. Moreover, the dimensionless pressure responses in drawdown for late times for different combinations can be estimated and are presented in Reference [11].

For any of the combinations considered and the well producing at a constant rate in the small compartment, the Cartesian derivative, p_{wD}' (or dp_{wD}/dt_D) during the appearance of the pseudosteady state, one can write,

$$p_{wD}' = 1 / (X_{0D}\, Y_{0D}) \qquad (1)$$

Dimensionalization of Eq. (1) yields,

$$N_p = q \,/\, |\, p_w' | \qquad (2)$$

where

$$N_p = \phi\, c_t\, V \,/\, B \qquad (3)$$

The value of p_w' can be read from the flattened intercept (plateau) in a plot of Cartesian derivative responses at the wellbore, p_w', versus time, t, on a Cartesian plot (or log-log plot). This value must correspond to the pseudosteady state (p_w' = non-zero constant). Figure 2 illustrates how these intercept values can be determined from a plot of p_w' versus t, drawn from a set of well-test data. Therefore, the hydrocarbon-pore volume in standard volume per unit drawdown pressure in the producing compartment can be estimated from the relationship in Eq. (2).

The method presented in this section has not been subject to any drastic simplifying assumption. On the contrary, *Fox et al.* [2] have suggested that the producing compartment possess a very high value to its hydraulic diffusivity to estimate the hydrocarbon-pore volume. Such an assumption has been meant to ignore the effects of transient flow before the entire system leads to the pseudosteady and/or steady state. But the method proposed in this article is applicable equally to any level of hydraulic diffusivity in the producing compartment.

(ii) Two-Compartment System

The idea presented for a system of a small compartment in communication with a big one can be extended to a cellular system with two compartments. *Rahman* [14] has shown that the transient-pressure responses at the wellbore in a two-compartment system are similar to those in the system considered earlier. Here, the

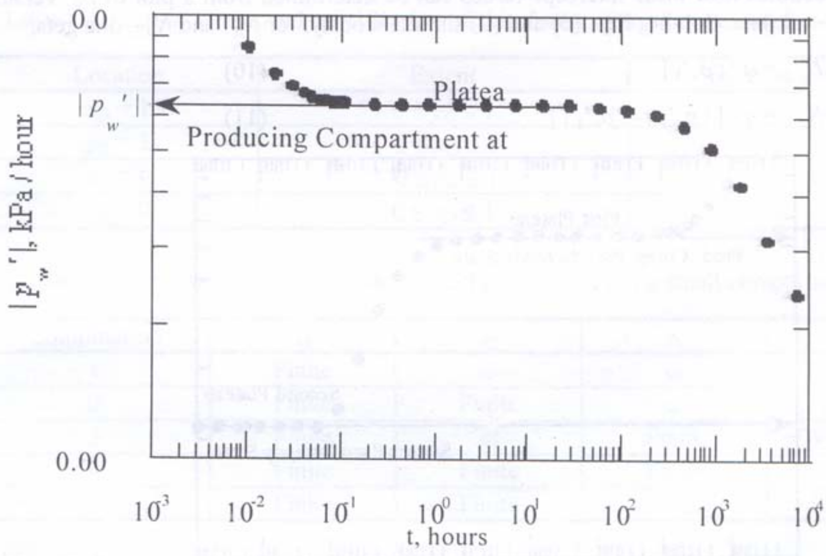

Fig. 2. Determination of intercept value from Cartesian derivative profile plotted with well test data from a compartmentalized system.

outer boundaries of the compartmentalized system are considered as closed ones. If one of the compartments is producing while the other is supporting through a partially communicating barrier, then the pressure responses at the producing compartment would lead to the pseudosteady state twice [14].

Taking advantage of this fact, one can derive the expressions for hydrocarbon-pore volumes as demonstrated below.

With the well producing at a constant rate in the first compartment, the Cartesian derivative, $p_{wD}'_1$ during the first appearance of the pseudosteady state is given by,

$$p_{wD}'_1 = q_D \, h_{pD} / e_1 A_1 \tag{4}$$

In this analysis, the reference parameters are taken with respect to the first compartment (producing compartment). Eventually the entire system undergoes the pseudosteady state. Then the late-time solution for the system stated above is given by,

$$p_{wD}'_2 = q_D \, h_{pD} / (e_1 A_1 + e_2 A_2) \tag{5}$$

Dimensionalization of Eqs. (4) and (5) yields,

$$p_w'_1 = -q / N_{p1} \tag{6}$$

$$p_w'_2 = -q / (N_{p1} + N_{p2}) \tag{7}$$

where,

$$N_{p1} = \phi_1 \, c_{t1} \, V_1 / B_1 \tag{8}$$

$$N_{p2} = \phi_2 \, c_{t2} \, V_2 / B_2 \tag{9}$$

The values of $p_w'_1$ and $p_w'_2$ are read from the first and second flattened intercepts (plateaus), respectively, in a plot of Cartesian derivative responses at the wellbore, p_w', versus time, t, on a Cartesian plot (or log-log plot). Figure 3 illustrates how these intercept values can be determined from a plot of p_w' versus t, drawn from a set of well-test data. Solving Eqs. (6) and (7) simultaneously, for N_{p1} and N_{p2}, one gets,

$$N_{p1} = q / |p_w'_1| \tag{10}$$

$$N_{p2} = q / [\, |p_w'_2| - |p_w'_1| \,] \tag{11}$$

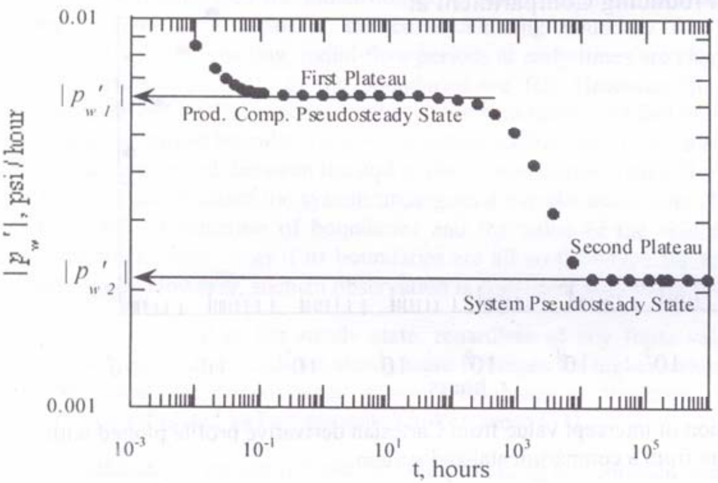

Fig. 3. Determination of intercept values from Cartesian derivative profile plotted with well test data for a two-compartment system.

Therefore, the hydrocarbon-pore volume in standard volume per unit drawdown pressure in each compartment ($N_{p\,1}$ and $N_{p\,2}$) is known, and the total hydrocarbon-pore volume in standard volume per unit drawdown pressure in the reservoir, N_p, can be computed from the following relationship,

$$N_p = N_{p\,1} + N_{p\,2} \qquad (12)$$

This method for estimating the hydrocarbon-pore volume in each compartment can be extended to any number of compartments, provided the corresponding number of plateaus are available on the p_w' versus t plot. The higher the resistance to flow at an interface (higher skin factor), the longer will be the corresponding pseudosteady-state period. As a result, the pseudosteady-state periods will look more prominent on the p_w' versus t plot. If one has some prior information about the formation volume factors and total compressibilities, then the respective hydrocarbon-pore volumes from Eqs. (8) and (9) can be determined.

Discussion

In the preceding sections, it has been shown that the hydrocarbon-pore volume can be estimated by analyzing the extended-drawdown data. Since this method is based on the pseudosteady state, it can be extended to other compartmentalized systems regardless of shape and size of the compartments. However, the evidence for a case of pseudosteady state corresponding to each compartment must be visible distinctly in the drawdown responses. Once this condition is met, the Eqs. (4) through (12) can be generalized intuitively for any number of compartments for computing the hydrocarbon pore volume for each compartment. In this analysis, it has been assumed that the entire pore space is saturated with hydrocarbons only. However, in the presence of any water saturation in the formation, some minor corrections are required for the formulae derived for the hydrocarbon-pore volumes.

Thus, a simple method has been proposed to compute the hydrocarbon-pore volumes by analyzing the extended-drawdown data. The number of data points that are required to be read from the p_w' versus t plot corresponding to each pseudosteady-state period (p_w' = constant) would be equal to the number of compartments. Using these values, hydrocarbon-pore volume in each compartment can be calculated using the equations derived earlier. An estimation of these values is very important for estimating the reserves in a field.

Conclusions

- Hydrocarbon-pore volumes can be estimated using the concept of pseudosteady state.
- A method has been proposed to analyze the extended-drawdown data for this purpose.

References

[1] Rahman, N.M.A. and Ambastha, A.K. A Generalized 3d analytical model for transient flow in compartmentalized reservoirs, paper SPE 38675 presented at the 72nd Annual Technical Conference and Exhibition of the SPE of AIME, San Antonio, TX, USA ,October, (1997).

[2] Fox, M.F., Chedburn, A.C.S. and Stewart, G. Simple characterization of communication between reservoir regions, paper SPE 18360 presented at the European Petroleum Conference of the SPE of AIME, London, UK. October, (1988).

[3] Lord, M.E. and Collins, R.E. Detecting compartmented gas reservoirs through production performance, paper SPE 22941 presented at the 66th Annual Technical Conference and Exhibition of the SPE of AIME, Dallas, TX, USA, October, (1991).

[4] Lord, M.E., Collins, R.E., Kocberber, S. and Kerr, D.R. A compartmented simulation system for gas reservoir evaluation with application to fluvial deposits in the frio formation, South Texas, paper SPE 24308 presented at the Mid-Continent Gas Symposium of the SPE of AIME, Amarillo, TX, USA , April, (1992).

[5] Junkin, J.E., Sippel, M. A. and Lord, M.E. Well performance for compartmented geometry of oil and gas reservoirs, paper SPE 24356 presented at the Rocky Mountain Regional Meeting of the SPE of AIME, Casper, WY, USA , May, (1992).

[6] Malavazos, M. and McDonough, R.C.M. Pressure-transient response in compartmentalized gas reservoirs: A South Australian Field Example, paper SPE 23009 presented at the Asia-Pacific Conference of the SPE of AIME, Perth, Western Australia, November, (1991).

[7] Lloyd, P.M., Koch, R., DesAutels, D., Zain, A.M. and Davis, R. Chasing channel sands in South East Asia, 'Proceedings of the 2nd Petroleum Engineering Symposium', Dhaka, Bangladesh, May, (1999).

[8] Stewart, G. and Whaballa, A. E. Pressure behavior of compartmentalized reservoirs, paper SPE 19779 presented at the 64th Annual Technical Conference and Exhibition of the SPE of AIME, San Antonio, TX, USA, October, (1989).

[9] Corapcioglu, M.Y., Borekci, O. and Haridas, A. Analytical solutions for rectangular aquifers with third-kind (cauchy) boundary conditions, 'Water Resources Research', 19(2), 523-528, Aprii, (1983).

[10] Rahman, N.M.A. and Ambastha, A. K. Transient-pressure behavior of compartmentalized reservoirs, paper SPE 38081 prepared for presentation at the Asia Pacific Oil and Gas Conference and Exhibition of the SPE of AIME, Kuala Lumpur, Malaysia, April, (1997).

[11] Rahman, N.M.A. and Ambastha, A. K. A Generalized transient-pressure model for areally-compartmentalized reservoirs, paper SPE 37340 presented at the Eastern Regional Meeting of the SPE of AIME, Columbus, OH, USA, October, (1996).

[12] Ambastha, A. K., McLeroy, P.G. and Grader, A.S. Effect of a partially communicating fault in a composite reservoir on transient pressure testing, 'SPE Formation Evaluation', 210-218 (June 1989).

[13] Ambastha, A. K. and Sageev, A. Linear water influx of an infinite aquifer through a partially communicating fault, 'Proceedings of the 12th Geothermal Reservoir Engineering Workshop', Stanford, CA, USA, January, (1987).

[14] Rahman, N.M.A. 'Transient-pressure analysis in compartmentalized reservoirs', Ph.D. dissertation, University of Alberta, Canada, 147-187, Spring, (1998).