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A PRACTICAL METHOD TO DETERMINE AQUIFER LEAKAGE FACTOR FROM WELL TEST DATA IN CBM RESERVOIRS

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ABSTRACT

Water influx is an important factor which needs to be quantified during early stages of reservoir development to justify project economics. For a CBM reservoir it is much more important to quantify degree of connection between Coal seams and aquifer (if any) as its production mechanism is based on efficient dewatering process. However, it is difficult to quantify connection factor values early in field life. Many traditional models ranging from simplest steady state model by Schilthuis and fetkovich utilizing material balance, to unsteady state solution of diffusivity equation by Van-Everdingen and Hurst exists for finding water influx but nearly all of them have inherit assumptions related to aquifer/reservoir boundray pressure or influx rate and requires accurate historical production data for estimation of correct influx which is often not available. However, during Appraisal/exploratory stage we do have accurate measurement of pressure at wellbore and production/injection rate when we conduct pressure transient testing. Well test analysis plays an important role in reservoir characterization and can aid in correct water influx calculations. Currently, pressure falloff test responses to quantify water influx in the reservoir with wells that exist near constant pressure boundary can be analyzed by either type-curve matching or non-linear regression analysis. The former is basically a trial-and-error procedure and the later can lead to incorrect/impractical results. So, we need a more robust and accurate methods for water influx calculation. In this work, a practical method is developed to interpret the injection-falloff test response for a CBM reservoir in connection with aquifer to quantify connection factor between aquifer and reservoir using pressure transient tests which are usually conducted during field appraisal/exploration phase. Besides complementing the conventional straight-line method for the determination the leakage factor, we also provide a solution using characteristic points found on the pressure, pressure derivative and second pressure derivative log-log plot of a ‘leaky aquifer’ reservoir model (Cox and Onsager, 2002) which allowed us to develop relationships for the accurate estimation the leakage factor. An extremely useful application of the second pressure derivative was also included for estimation the unknown reservoir permeability for cases in which radial flow regime is completely masked by other flow regimes. The provided interpretation methodologies were successfully tested with synthetic examples.

Keywords: aquifer permeability, water influx, reservoir characterization, leakage factor, CBM.

INTRODUCTION

Unconventional gas reservoirs have become an integral part of energy supply basket due to ever increasing demand of oil and gas and decrease in new conventional discoveries. In future, these unconventional reservoirs are expected to become more significant as era of conventional/easy oil and gas comes to an end. So it is vital to devise new methods for characterization of these complex reservoirs because accurate knowledge is not present about their production mechanism and performance with time.

Coalbed methane (CBM) has developed into an important part of unconventional resources. At the time reservoir is discovered, nearly all hydrocarbon reservoirs are surrounded by porous rock containing water - Schafer, Hower and Ownes (1993), CBM reservoirs mostly contain natural fractures called cleats which are in most cases filled with water, since CBM reservoirs operate on principle of desorption of gas from coal seam surface due to depressurization, most CBM reservoirs require efficient dewatering before they can produce commercial volume of gas -Onsager and Cox (2000). In some instances, water influx from other aquifer units can inhibit the dewatering of the coal and thereby limit coal bed methane recovery - Onsager and Cox (2000). So it becomes extremely important to come up with new methods to characterize the degree of connection between these coals and other units early in field life. It has been long recognized in groundwater industry that many aquifer have imperfect seals and are in connection with other aquifer units through a low permeability confining layer -Cox and Onsage, (2002), particularly for shallow reservoirs like CBM small aquifers connected with reservoir can be in communication to other aquifer units through low permeability “leaky” confining layers, this implies aquifer connection with reservoir is not perfect ($\Delta P_{res.} \neq \Delta P_{aquifer}$).

Traditional Methods used in Petroleum Industry for water Influx quantification like fetkovich and Schilthuis utilizes material balance with assumption of $\Delta P_{res.} = \Delta P_{aquifer}$, whereas Van Everdingen-Hurst (VEH) is based on diffusivity equation and gives solution for conditions of constant terminal water influx and constant terminal pressure at aquifer reservoir boundary for radial models. Carter-Tracy method is just modification over

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VEH to save computation time. According to Fetkovich, M.J. (1971) “The last three methods have proved useful for predicting water drive performance after suffient historical data have been obtained to fix necessary influx constants with what some consider to be disappointing”. Coats (1962) and Allard and Chen (1988) considered 2-D model to provide water influx solutions for bottom water drive reservoir with constant terminal rate and pressure case. Some other recently developed methods like GRACE transform by Al-ghanim, Nashawi & Malallah, (2012) can also be used for water influx calculations. However, all methods are based on either constant terminal pressure at aquifer/reservoir boundary or constant terminal influx rate which may or may not be true. In 2002, Cox and Onsager took a slightly different approach than VEH to obtain solutions for diffusivity equation, for a CBM reservoir connected with aquifer. Which could be easily used in pressure transient testing to come out with amount of pressure support provided by aquifer. This information can be very critical before incorporating any water influx models for calculation of amount of water influx. The constant terminal rate boundary condition (as during falloff/buildup rate =0) is much valid at well location rather than at aquifer/reservoir boundary which VEH assumed. In this Paper we build-up on solutions given by Cox and Onsager, 2002 for pressure falloff test and present a new method that can provide a more practical way to quantify aquifer reservoir connectivity for a reservoir with bottom water drive early in field life using pressure transient data.

Hantush and Jacob (1955) published a methodology known in groundwater industry as “leaky aquifer model”. The idealized Hantush-Jacob leaky aquifer model assumes a constant pressure boundary at top/bottom of confining layer. ‘Leaky aquifer’ models more accurately describes bottom/top water drive CBM reservoirs in which coal is only producing layer this case can also be modelled by methods given by Neuman, S.P. and P.A. Witherspoon (1972) and Guo, Stewart and Toro (2002) which is essentially same as that of Hantush and Jacob (1955). Hantush and Jacob (1955) developed solution for non-steady distribution of drawdown caused by pumping a well at a constant rate from an effectively infinite and perfectly elastic aquifer of uniform thickness in which leakage takes place in proportion to the drawdown. They came up with parameter ‘b’ called as ‘leakage factor’ which is a function of hydraulic conductivity and thickness of confining bed through which leakage occurs. Leakage coefficient is defined as “the quantity of flow that crosses a unit area of the interface between the main aquifer and its semi- confining bed, if the difference between the head in the main aquifer and in that supplying leakage is unity” -Hantush (1956).

Using Laplace transform method Cox and Onsager (2002) came up with dimensionless pressure solutions for diffusivity equations of ‘Leaky Aquifer’ model, and demonstrated the application of leaky aquifer model to injection falloff transient test in CBM wells with use of type curves to quantify leakage factor of aquifer in reservoir. In this paper, based on solutions given by Cox and Onsager, we propose a more practical method which uses characteristics points found on pressure and second pressure derivatives log-log curve and try to demonstrate the robustness of proposed method using synthetic pressure falloff data for a CBM reservoir.

The objective of this paper is to provide newer ways for analytically characterizing the ‘leakage factor’ from a pressure test which is defined as degree of connection between strong aquifer unit and main reservoir. First, the conventional analysis method was implemented to find such parameter based upon the steady-state pressure drop which can be easily found from either the Cartesian or semilog or log-log plot of pressure versus time. Next, we formulated a practical technique to find the leakage factor using the maximum point found on the second pressure derivative once radial flow is vanished. A practical equation for the determination of reservoir permeability was also introduced using the mentioned maximum point. Such methodology uses the *TDS* technique introduced by Tiab (1995). We use two characteristic features (maximum pressure derivative and intersection between both derivatives) to develop four expressions for estimating the leakage factor. We also unified the late steady-state curve by multiplying the time by the leakage factor, so an expression using a negative two slope was developed for the leakage factor determination. The potential use of the second derivative was used to find a new expression to estimate permeability from the maximum second pressure derivative which is so vital for cases when the radial flow is unseen. The equations were successfully verified by using synthetic examples.

Model description leaky aquifer concept

An ideal leaky aquifer model is depicted in Figure-1. Three layers are considered Producing Layer, Confining Layer and Aquifer layer which provides pressure support to main producing layer through a confining layer. It is interest to quantify amount of pressure support provided by aquifer to main reservoir.

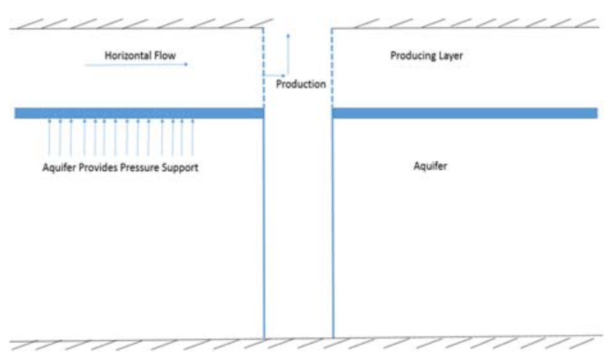

Figure-1. Schematic of a leaky aquifer model.

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Assumptions for leaky aquifer model

No free gas present, so single phase flow of only water is occurring in the reservoir. Various layers are homogenous and have uniform reservoir properties and Rock Compressibility is negligible. The pressure at bottom of confining layer is constant because of aquifer support (Cox and Onsager, 2002). Vertical permeability of supporting aquifer is similar to horizontal permeability also capillary and gravity effects are ignored.

Radial flow analysis

The solution for Laplace transform of wellbore pressure for a leaky aquifer model Equation (1) was provided by Cox and Onsager (2002) .This formula was inverted using Stehfest algorithm to obtain dimensionless pressure and time curves for well with no wellbore storage and skin having different values of leakage factor ranging from $1x10^{-2}$ to $1x10^{-6}$. At early time, curves show characteristic radial flow behavior with zero slope but depending on the quantity of support from aquifer the pressure tends to steady state which causes derivative to drop to zero. In some cases leakage factor may be too large that there is no stable derivative portion for radial flow analysis.

DISCUSSIONS

Type curve analyses have several disadvantages for estimation of accurate reservoir properties. We demonstrate the utility of TDS and the application of the second derivative for estimation of accurate reservoir parameters especially 'leakage Factor' for a leaky aquifer model in a homogenous layered reservoir with help of two synthetic examples.

Example 1 demonstrates an important point about utility of our method which uses intersection point of first and second derivative for obtaining critical reservoir parameters in cases where radial flow is partially masked by wellbore storage.

MATHEMATICAL FORMULATION

Mathematical model

Onsager and Cox (2002) provided the solution of the diffusivity equation with wellbore storage and skin in Laplace space for a reservoir with an underlying leaky aquifer,

$$\overline{P_D} = \frac{1}{\ell} \frac{K_o(\sqrt{u}) + s\sqrt{u}K_1(\sqrt{u})}{\sqrt{u}\,K_1(\sqrt{u}) + \ell^2 C_D\left[K_o(\sqrt{u}) + s\sqrt{u}K_1(\sqrt{u})\right]} \qquad (1)$$

in which;

$$u = \ell + b_D \qquad (2)$$

$$b = \frac{k_{v,conf}}{h_{conf}} \qquad (3)$$

$$b_D = \frac{k_{v,conf}\, r_w^2}{khh_{conf}} \qquad (4)$$

The dimensionless quantities are defined below as:

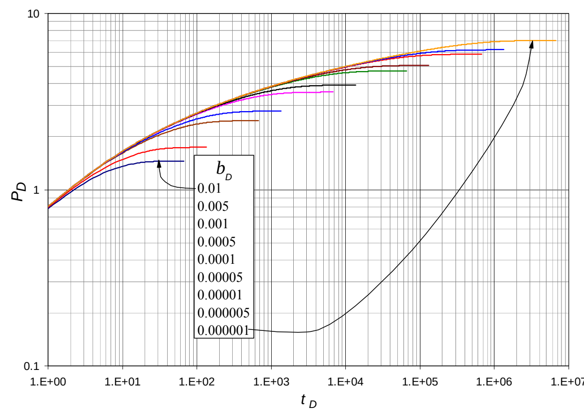

Figure-2. Dimensionless pressure versus time log-log behavior for several values of dimensionless leakage factors.

$$t_D = \frac{0.0002637kt}{\phi\mu c_t r_w^{\ 2}} \qquad (5)$$

$$P_D = \frac{kh\Delta P}{141.2q\mu B} \qquad (6)$$

$$t_D * P_D' = \frac{kh(t*\Delta P')}{141.2q\mu B} \qquad (7)$$

$$t_D^2 * P_D'' = \frac{kh(t^2*\Delta P'')}{141.2q\mu B} \qquad (8)$$

Conventional analysis

Figure-2 presents the dimensionless pressure behavior obtained from Equation (1). In this log-log plot it is observed that the steady state is reached at a different time depending on the leakage factor value. Actually, these values are correlated as observed in Figure-3. A strong dependency of the pressure at which steady state takes places on leakage factor is clearly observed and established as given below:

$$b_D = 1.5338e^{-0.014413\left(\frac{kh\Delta P_{ss}}{q\mu B}\right)} \qquad (9)$$

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Therefore, from a log-log plot of dimensionless pressure drop versus dimensionless time is easy to observe that the pressure drop is constant once the steady state is fully developed. However, any conventional plot, for example, semilog or Cartesian, can be used to find the steady-state pressure by drawing a horizontal line on the late steady-state period and finding the intercept on the *y*-axis. In any case, this is observed by a flat behavior of either pressure or pressure drop. This value is read and replaced into Equation (10) to easily obtain the leakage factor. It is worth to remind that unlike pressure derivative, pressure drop is sensitive to skin effect; then, ΔP_{ss} in Equation (9) has to be free of skin effects. This means that:

$$\Delta P_{ss} = P_i - P_{wf} - \Delta P_s \tag{10}$$

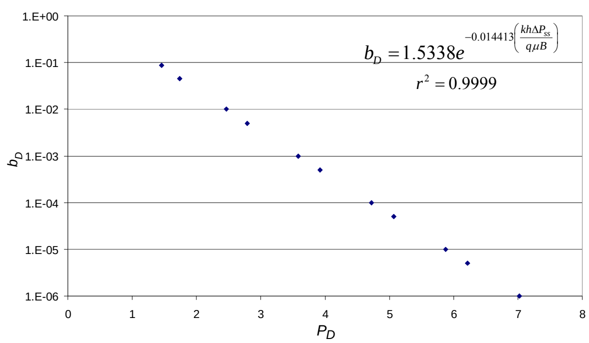

Figure-3. Behavior of the leakage factor as a function of the pressure drop during steady-state.

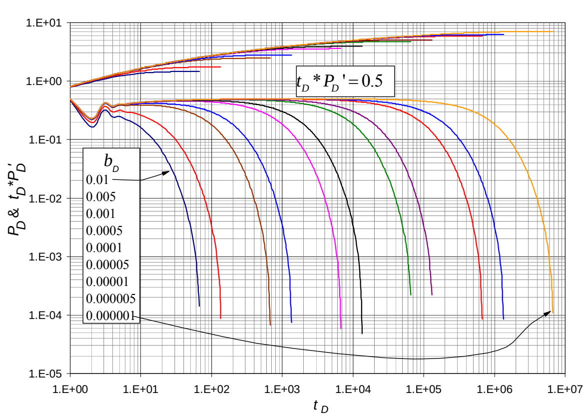

Figure-4. Dimensionless pressure and pressure derivative versus time log-log behavior for several values of dimensionless leakage factors.

$$\Delta P_{ss} = P_{ws} - P_{wf} - \Delta P_s \tag{11}$$

Equation (10) is applied to drawdown and Equation (11) is applied to buildup tests.

Additionally, the equivalent time proposed by Agarwal (1980) is recommended to be used in buildup tests.

TDS technique

This technique was introduced by Tiab (1995) and is based upon specific features found on the pressure and pressure derivative versus time log-log plot.

For the case dealt in this paper refer to Figure-4 to observe the dimensionless pressure and pressure derivative behavior. It is seen that during radial flow regime the pressure derivative is governed by a flat straight line (zero slope) with an intercept of 0.5. Tiab (1995) demonstrated that after Equation (7) is equalized to 0.5, an expression to find permeability is given:

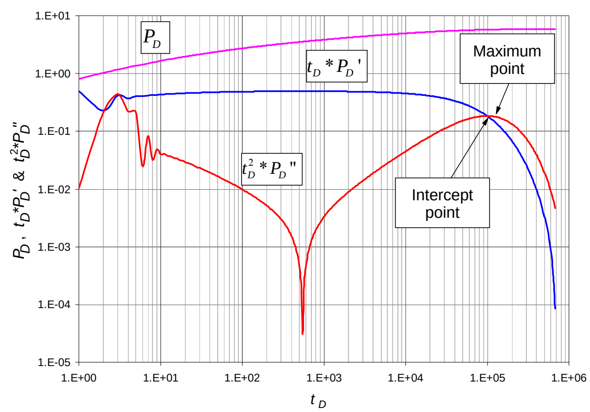

Figure-5. Dimensionless pressure, pressure derivative and second pressure derivative versus time log-log plot for $b_D = 0.00001$.

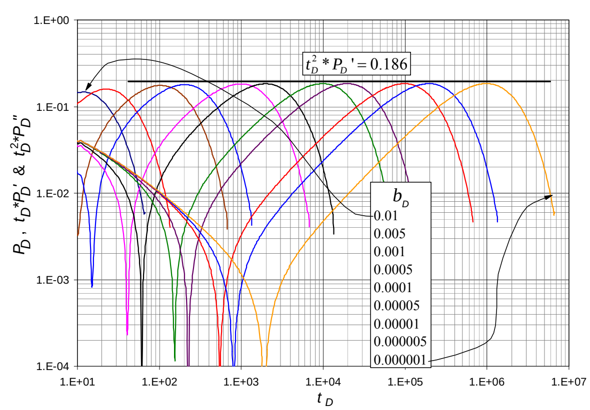

Figure-6. Dimensionless pressure, pressure derivative and second pressure derivative versus time log-log plot for several values of dimensionless leakage factors.

$$k = \frac{70.6 q\mu B}{h(t*\Delta P')_r} \tag{12}$$

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Tiab (1995) also provided an expression to find the skin factor by reading the pressure drop at any arbitrary time during radial flow:

$$s = 0.5\left(\frac{\Delta P_r}{(t*\Delta P')_r} - \ln\left[\frac{k\,t_r}{\phi\mu c_t r_w^2}\right] + 7.43\right) \tag{13}$$

However, for the interest of this work, the pressure derivative does not help much since it has a decaying behavior as seen in Figure-5. Then, besides pressure and pressure derivative given in Figure-5, Figure-6 also includes the second pressure derivative behavior. in both plots two characteristic features are clearly seen: (1) a point of intersection between derivative and second derivative, and (2) a maximum point displayed by the pressure derivative which is given in Figure-6 for other cases studies.

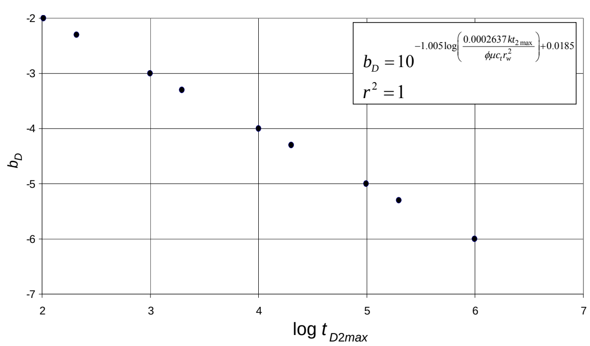

Figure-7. Correlation between the time at which the maximum value of the second derivative takes place and the leakage factor.

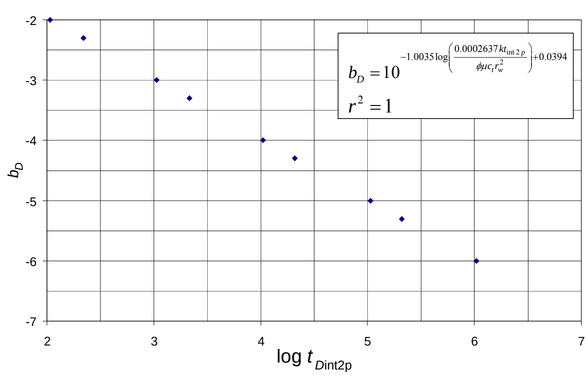

Figure-8. Correlation between the time at which the pressure and second pressure derivatives intercept and the leakage factor.

Several observations can be drawn from Figure-6. The first one is that the maximum points are function of time and second derivative is practically constant at a dimensionless value of 0.186. Then:

$$t_D^2 * P_D'' = \frac{kh(t^2*\Delta P'')}{141.2q\mu B} \approx 0.186 \tag{14}$$

Solving for permeability:

$$k \approx \frac{26.2632q\mu B}{h(t^2*\Delta P'')_{2\max}} \tag{15}$$

Equation (15) may be the practical use whenever the radial flow regime is obscured by wellbore storage.

The second observation is better explained in Figure-7 where a perfect correlation between time and leakage is obtained and given below:

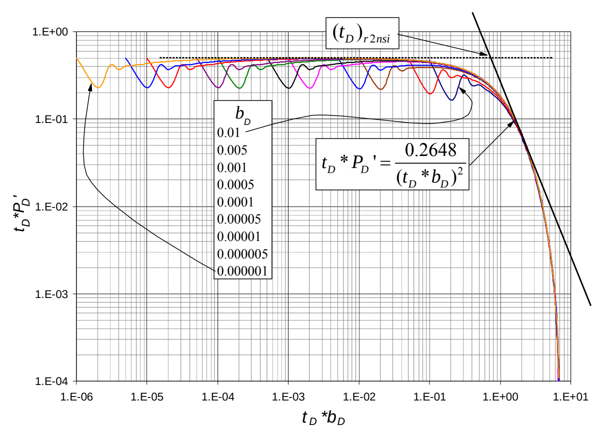

Figure-9. Log-log plot Dimensionless pressure derivative a versus dimensionless time multiplied by dimensionless leakage factor.

$$b_D = 10^{-1.005\log\left(\frac{0.0002637kt_{2\max}}{\phi\mu c_t r_w^2}\right)+0.0185} \tag{16}$$

Third, for cases where the maximum point is difficult to be seen, probably due to much noise, and the intercept between the two derivatives is seen, a perfect correlation is reported in Figure-8. The obtained correlation is provided below:

$$b_D = 10^{-1.0035\log\left(\frac{0.0002637kt_{\text{int}\,2p}}{\phi\mu c_t r_w^2}\right)+0.0394} \tag{17}$$

The fourth and final observation in Figure-6 allows seeing a dependency of leakage factor on both time and second derivative, although the last one has a weak dependency. Equation (16) is a final correlation of the leakage factor as a function of pressure derivative and time read at the maximum point. However, for easier manipulations, the second pressure derivative is divided by the pressure derivative during radial flow regime. If

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this is unclear and permeability is known, then, pressure derivative can be solved from Equation (12).

$$Z = 0.0491070542313 - 2.2954373F1 - 6.6837964356\times10^{-03}F2 \quad (18)$$

where,

$$F1 = 1/\log\left(\frac{0.0002637kt_{2\max}}{\phi\mu c_t r_w^2}\right) \quad (19)$$

$$F2 = \left(\frac{(t*\Delta P')_r}{(t^2*\Delta P'')_{2\max}}\right)^2 \quad (20)$$

$$b_D = 10^{1/Z} \quad (21)$$

A final observation comes out from Figure-9 which is a log-log plot of dimensionless pressure derivative versus the product of dimensionless time multiplied by the dimensionless leakage factor. As seen in the plot the late steady-state period unifies into a single line. So, drawing a straight line of a slope of -2 will yield to the following fitting:

$$t_D * P_D' = \frac{0.2648}{(t_D * b_D)^2} \quad (22)$$

The intercept of Equation (22) with the radial flow regime pressure derivative (t_D*P_D'=0.5) provides the following expression:

$$b_D = \frac{2759.713\phi\mu c_t r_w^2}{kt_{r2nsi}} \quad (23)$$

being t_{r2nsi} the point of intersect between the radial flow and the negative two-slope lines.

EXAMPLES

Synthetic example 1

A simulated test was performed using Onsager and Cox (2002) model with the below information:

B = 1.005 bbl/STB	q = 30 STB/D
h = 200 ft	μ = 1 cp
r_w = 0.4 ft	c_t = 1x10^{-4} psi^{-1}
P_i = 3500 psi	ϕ = 30 %
k = 10 md	b_D = 0.00035
C_D = 10	s = 1

Pressure, pressure derivative and second pressure derivative versus time are provided in Figure-10. It is required to characterize this test with the sole purpose of estimating the leakage factor.

Solution by conventional analysis

Actually, this example cannot be solved by conventional analysis since both wellbore storage and aquifer effects mask the radial flow regime. Therefore, neither skin factor nor permeability can be determined. However, assuming both permeability and skin factor is known, then, from the log-log plot of ΔP vs. t, Figure-10, the value at which the horizontal line is drawn during the late steady-state period intercepts the y-axis is:

$$\Delta P_{ss} + s = 10.853 \text{ psi}$$

There is a need of finding the semilog slope from the classic permeability equation in order to find the pressure drop due to skin factor:

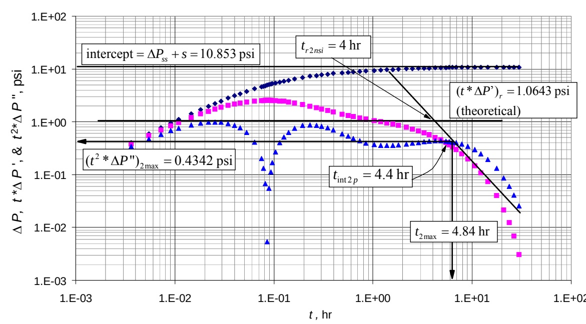

Figure-10. Log-log plot of pressure, pressure derivative and second pressure derivative versus time for example 1.

$$k = \frac{162.6q\mu B}{hm} \quad (24)$$

Solving for m;

$$m = \frac{162.6q\mu B}{hk} = \frac{162.6(30)(1)(1.005)}{(200)(10)} = -2.4512 \text{ psi/cycle}$$

Since:

$$\Delta P_s = \pm 0.87ms = \pm 2s(t*\Delta P')_r \quad (25)$$

The pressure drop due to a skin factor of one is 2.133. Then, ΔP_{ss}= 8.72 psi which used in Equation (9) will provide:

$$b_D = 1.5338e^{-0.014413\left(\frac{(10)(200)(8.72)}{(30)(1)(1.005)}\right)} = 0.000375$$

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Solution by *TDS* Technique

The following information was read from Figure-10:

t_{r2nsi} = 4 hr t_{int2p} = 4.4 hr
t_{2max} = 4.84 hr $(t^2*\Delta P")_{2max}$ = 0.4342 psi

This is a very common case where the radial flow is obscured by wellbore storage. Besides, the steady-state period also contributes to not having a well-defined radial flow regime line. Then, the second derivative at the maximum point can also be used to estimate permeability from Equation (15):

$$k \approx \frac{26.2632(30)(1)(1.005)}{(200)(0.4342)} = 9.2 \approx 10 \text{ md}$$

Since we need the value of pressure derivative during radial flow regime -actually it can be obtained from Equation (25)-, then, it is estimated from Equation (12):

$$(t*\Delta P')_r = \frac{70.6 q\mu B}{hk} = \frac{70.6(30)(1)(1.005)}{(200)(10)} = 1.0643 \text{ psi}$$

The leakage factor can be found from Equations (16) and (17), respectively:

$$b_D = 10^{-1.005\log\left(\frac{0.0002637(10)(4.85)}{(0.3)(1)(0.0001)(0.4^2)}\right)+0.0185} = 0.000372$$

$$b_D = 10^{-1.0035\log\left(\frac{0.0002637(10)(4.4)}{(0.3)(1)(0.0001)(0.4^2)}\right)+0.0394} = 0.00044$$

Finally, using the coordinates of the maximum point of the second derivative in Equations (18) through (21), the leakage factor is also obtained:

$$F1 = 1/\log\left(\frac{0.0002637(0.1)(1298.48)}{(0.3)(1)(0.0001)(0.4^2)}\right) = 0.127$$

$$F2 = \left(\frac{1.064}{0.432}\right)^2 = 6.25$$

$$Z = 0.0491070542313 - 2.2954373(0.127)$$
$$- 6.6837964356\times10^{-03}(6.25) = -0.284$$

$$b_D = 10^{-1/0.2822} = 0.0003$$

The point of intersection between the radial flow regime and the negative two- slope lines is also used to find leakage factor from Equation (23);

$$b_D = \frac{2759.713(0.3)(1)(0.0001)(0.4^2)}{(10)(4)} = 0.000331$$

Synthetic example 2

Another pressure test was simulated with the below information:

B = 1.00 bbl/STB q = 550 STB/D
h = 150 ft μ = 0.5 cp
r_w = 0.5 ft c_t = 5x10^{-5} psi^{-1}
P_i = 3850 psi ϕ = 20 %
k = 60 md b_D = 0.000038
C_D = 0 s = 0

Figure-11 presents the semilog plot of pressure versus time and Figure-12 contains a log-log plot of pressure drop, pressure derivative and second pressure derivative versus time. Find permeability, skin factor and the leakage factor using both conventional analysis and *TDS* technique.

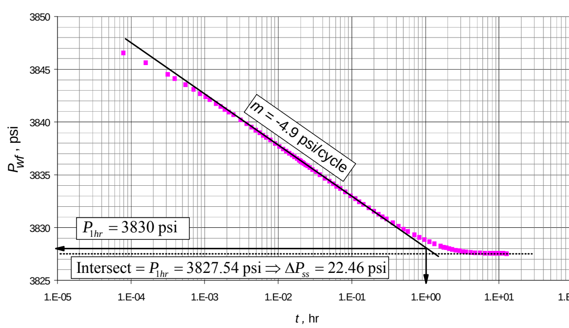

Figure-11. Semilog plot of pressure versus time example 2.

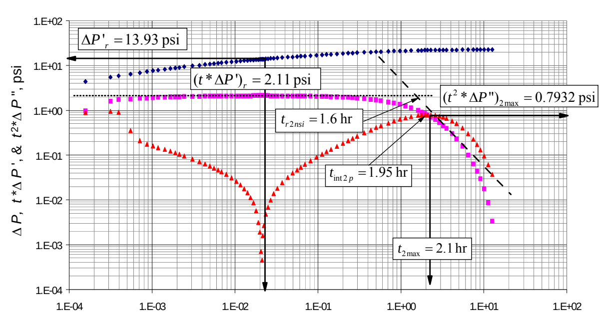

Figure-12. Log-log plot of pressure, pressure derivative and second pressure derivative versus time for example 2.

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Solution by conventional analysis

The following information is read from the semilog plot reported in Figure-10.

m = -4.9 psi/cycle
P_{1hr} = 3830 psi
ΔP_{ss}= 22.46 psi

Permeability and skin factor are found with Equations (24) and (25), respectively.

$$k = \frac{162.6(550)(0.5)(1)}{(150)\left|-4.9\right|} = 60.84 \text{ md}$$

$$s = 1.1513\left[\frac{P_{1hr} - P_i}{m}\log\left(\frac{k}{\phi \mu c_t r_w^2}\right) - 3.23\right] \quad (25)$$

$$s = 1.1513\left[\frac{3830-3850}{-4.9}\log\left(\frac{60.84}{(0.2)(0.5)(0.00005)(0.5^2)}\right) - 3.23\right]$$
$$s = -0.43$$

The steady-state period is easily observed in both plots, Figures-11 and -12. Recalling the constant pressure value read from Figure-11 (ΔP_{ss}= 22.46 psi): the leakage factor is found from the application of Equation (9);

$$b_D = 1.5338 e^{-0.014413\left(\frac{(60.84)(150)(22.46)}{(550)(0.5)(1)}\right)} = 0.0000385$$

Solution by *TDS* Technique

The following information was read from Figure-12:

t_{int2p} = 1.95 hr t_{2max} = 2.1 hr
$(t^2 * \Delta P'')_{2max}$ = 0.7932 psi t_r = 0.0224 hr
$(t * \Delta P')_r$ = 2.11 psi ΔP_r = 13.93 psi
t_{r2nsi} = 1.6 hr

Using the value of the pressure derivative during radial flow regime, permeability is easily found from Equation (12);

$$k = \frac{70.6(550)(0.5)(1)}{(150)(2.1)} = 61.3 \text{ md}$$

Taking an arbitrary point during the radial flow regime, skin factor is estimated with Equation (13);

$$s = 0.5\left(\frac{13.93}{2.11} - \ln\left[\frac{61.3(0.0224)}{(0.2)(0.5)(0.00005)(0.5^2)}\right] + 7.43\right)$$
$$s = 0.06$$

Making use of the time at which the maximum second pressure derivative takes place find the leakage factor from Equation (16);

$$b_D = 10^{-1.005\log\left(\frac{0.0002637(61.83)(2.11)}{(0.2)(0.5)(0.00005)(0.5^2)}\right) + 0.0185} = 0.0000365$$

Using the time of intersection between the derivatives find the leakage factor with Equation (17);

$$b_D = 10^{-1.0035\log\left(\frac{0.0002637(61.83)(1.95)}{(0.2)(0.5)(0.00005)(0.5^2)}\right) + 0.0394} = 0.000042$$

Find the leakage factor from the application of the coordinates of the maximum point of the second derivative with Equations (18) through (21)

$$F1 = 1/\log\left(\frac{0.0002637(61.83)(2.1)}{(0.2)(0.5)(0.00005)(0.5^2)}\right) = 0.09815$$

$$F2 = \left(\frac{2.11}{0.7932}\right)^2 = 7.407$$

$$Z = 0.0491070542313 - 2.2954373(0.09815)$$
$$- 6.6837964356 \times 10^{-03}(7.407) = -0.2257$$

$$b_D = 10^{-1/0.2822} = 0.0000371$$

The point of intersection between the radial flow regime line and the negative two-slope line is used to find another value of leakage factor from Equation (23);

$$b_D = \frac{2759.713(0.2)(0.5)(0.00005)(0.5^2)}{61.83(1.6)} = 0.000035$$

COMMENTS ON THE RESULTS

The results obtained from both techniques are quite satisfactory. Although, the conventional analysis provides a single finding of the leakage factor, the results were excellent in both exercises, even though, the first problem cannot be completely carried out by conventional technique due to the missing of the radial flow regime.

As far as the use of the *TDS* technique is concerned, four different forms for estimating the leakage factor are provided. The best results were obtained from

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the use of the time at which the maximum point displayed by the second derivative takes place. The expression that uses the intersect point formed between the two derivatives provided less accurate results, due to the fact that it is difficult to exactly define such intercept. The solution provided by Equation (18) through (21) provided better results in the second problem. It may be due to the fact that wellbore storage could affect the solution. In both exercises the solution found with Equation (23) which uses the intercept between the radial line and the negative two-slope line (artificially added) provided excellent results.

It is worth to remark that the maximum point of the second pressure derivative was also used to find an approximation for the determination of permeability. The first example is a typical case of its use since the radial flow was undefined.

CONCLUSIONS

a) New expressions were introduced for the determination of the leakage factor by using both conventional analysis and the *TDS* technique. A total of five expressions were introduced four of which belong to the *TDS* technique. The expressions were satisfactory applied to synthetic examples.
b) The *TDS* technique used the potential of the second derivative for the estimation of the leakage factor. The maximum point of the second pressure derivative was also used to provide an approximation to find reservoir permeability.
c) The value of leakage factor found out by presented new methods lead to better estimation and is much more robust than using type-curve analysis which may lead to inaccurate estimations.
d) Further analysis and historical data is needed to show that the calculated leakage factor values can be used in classic diffusivity equation to estimate accurate amount of water influx which can be compared with VEH water influx model to test its validity.

Nomenclature

B	Volume factor, rb/STB
b	Leakage factor, ft
C	Wellbore storage coefficient, bbl/psi
c_t	Total system compressibility, psi^{-1}
h	Reservoir thickness, ft
ℓ	Laplace parameter
k	Reservoir permeability, md
P	Pressure, psi
P_i	Initial reservoir pressure, psi
P_{wf}	Wellbore flowing pressure, psi
q	Water flow rate, BPD
r_w	Wellbore radius , ft
s	Skin factor
t	Time, days
t_D	Dimensionless time coordinate
t_D*P_D'	Dimensionless pressure derivative
$t_D^2*P_D''$	Dimensionless second pressure derivative
$(t*\Delta P')$	Pressure derivative
$(t^2*\Delta P'')$	Second pressure derivative

e) **Greeks**

f)

ϕ	Porosity, fraction
μ	Viscosity, cp

g)

h) **Suffices**

i)

2*max*	Maximum of the second pressure derivative
conf	Confining layer
D	Dimensionless
i	Initial
*int*2*p*	Intercept of pressure derivative and second pressure derivative
r	Radial
*r*2*nsi*	Intersect of the radial flow line and the negative two-slope line
ss	Steady state
v, conf	Vertical in confining layer

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