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ON THE DETERMINATION OF THE AQUIFER LEAKAGE FACTO IN CBM INFINITE RESERVOIRS USING TRANSIENT PRESSURE ANALYSIS

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ABSTRACT

The estimation of water influx from a surrounding aquifer into a Coalbed Methane (CBM) reservoir is a key parameter in an appropriate reservoir characterization activity since the degree of connection between natural fractures with other reservoir units has an economic impact. The solution of the traditional diffusivity equation for water influx cases has been somehow extended to CBM reservoirs so several ways of estimation the aquifer leakage factor has been introduced; including type-curve matching which involves trial-and-error processes. In this work, three expressions for the estimation of the aquifer leakage factor of CBM reservoirs are introduced using transient pressure analysis by reading characteristic featured taken from the pressure, pressure derivative and second pressure derivative versus time log-log plot. These equations were successfully tested with synthetic examples obtaining absolute deviation errors, in the worst scenario, lower than 10% which is very good for a parameter with such very small values. However, the best results provided errors lower than 1%.

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

1. INTRODUCTION

Coalbed methane reservoirs are surrounded by an aquifer and possess natural fractures referred as cleats which are normally filled with water as described by Schafer, Hower and Ownes (1993). The production comes by gas desorption from coal seam due to depressurization so efficient dewatering is required before production of commercial gas volumes as expressed by Onsager and Cox (2000). An adequate reservoir characterization is very important so the degree of between these coals and other reservoir elements can be accurately estimated.

Van Everdingen and Hurst (1949) solved the traditional diffusivity equation and gave solution for both constant water influx and constant pressure conditions at aquifer reservoir boundary for radial models. As far as transient pressure analysis is concerned, the first approach was given by Cox and Onsager (2002) who used a variation of the model by Van Everdingen and Hurst (1949) to be extended to CBM reservoir surrounded by an aquifer. Another approach was proposed by Hantush and Jacob (1955) which model assumed a constant pressure boundary at top and bottom of the confining layer. Methods to account for leaky aquifer models accounting for bottom/top water drive CBM reservoirs were presented by Neuman and Witherspoon (1972) and Guo, Stewart and Toro (2002) which is has a slight variation of the work by Hantush and Jacob (1955).

This paper is an extension of the work by Escobar, Srivastava and Wu (2015) who accurately estimated the aquifer leakage factor in Coalbed methane (CBM) reservoirs using the *TDS* Technique, Tiab (1995), for finite reservoirs. The main objective was the estimation of the aquifer leakage factor in infinite CBM reservoir surrounded by an aquifer. The obtained results were very much alike those used as simulation input.

2. MATHEMATICAL FORMULATION

2.1 Mathematical Model

Cox and Onsager (2002) provided the solution in Laplace space of the wellbore pressure for radial flow in a leaky aquifer system with wellbore storage and skin,

$$\overline{P_{wD}} = \frac{K_o(\sqrt{u}) + S\sqrt{u}K_1(\sqrt{u})}{s\sqrt{u}\,K_1(\sqrt{u}) + s^2 C_D\left[K_o(\sqrt{u}) + S\sqrt{u}K_1(\sqrt{u})\right]} \quad (1)$$

in which;

$$u = s + b_D \quad (2)$$

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

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

The dimensionless quantities are defined below as:

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

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

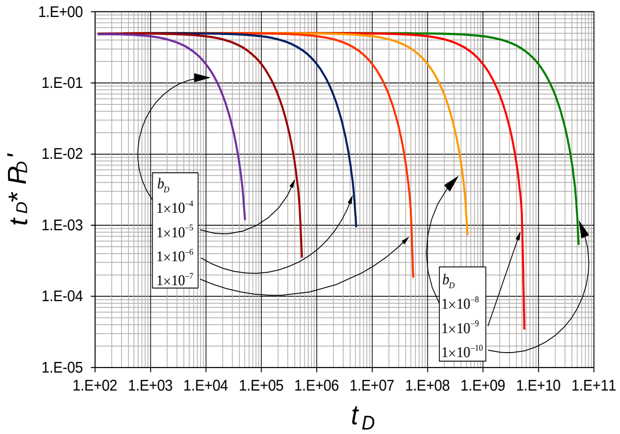

Figure-1. Pressure derivative versus time log-log behavior for several values of dimensionless leakage factors.

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

2.2 TDS Technique

Tiab (1995) presented this technique which is based upon characteristic points found on the pressure and pressure derivative versus time log-log plot.

Regarding the case exposed in this paper, observe in Figure-2, this feature is also seen in Figure-1, the dimensionless pressure and pressure derivative behavior. Note that the pressure derivative is distinguished by a flat straight line (zero slope) with an intercept of 0.5 during the radial flow regime. Once Equation (7) is equalized to 0.5, an expression to find permeability was introduced by Tiab (1995):

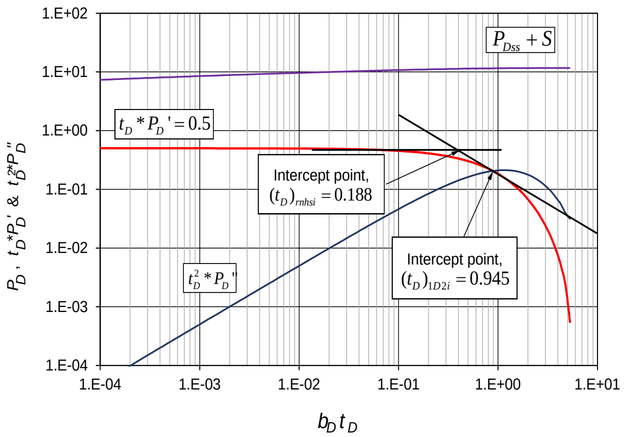

Figure-2. Dimensionless pressure, pressure derivative and second pressure derivative versus the product of dimensionless time multiplied by the dimensionless leakage factor log-log plot for b_D = 1.E-10.

$$k = \frac{70.6 q\mu B}{h(t*\Delta P')_r} \tag{8}$$

In addition, Tiab (1995) found an expression to determine the skin factor during radial flow by taking the pressure drop, ΔP_r, reading at any arbitrary time, t_r:

$$S = 0.5\left(\frac{\Delta P_r}{(t*\Delta P')_r} - \ln\left[\frac{k\, t_r}{\phi\mu c_t r_w^2}\right] + 7.43\right) \tag{9}$$

Figure-1 presents the pressure derivative behavior obtained from Equation (1). In this log-log plot it is observed that depending upon the leakage factor value, the steady-state period is reached at a different time.

A normalized pressure derivative behavior is found by multiplying the dimensionless time by the dimensionless aquifer leakage factor as reported in Figure-2. Such figure also includes three specific features which are easily appreciated: (1) a point of intersection between the dimensionless pressure derivative and the dimensionless second pressure derivative, and (2) a point of intersection between radial flow and an artificially drawn straight line of a slope of -0.5 passing tangent to the pressure derivative. This -0.5-slope straight line is strategically drawn to obtain the characteristic point with the shortest testing time. The first characteristic point has a dimensionless time value of 0.945. Then:

$$b_D = \frac{3583.62\phi\mu c_t L_c^2}{k t_{1D2i}} \tag{10}$$

The second intersection mentioned, according to the plot, is equivalent to a dimensionless time value of 0.188, so if this is set equal to Equation (5), it provides the following expression:

$$b_D = \frac{712.5521\phi\mu c_t L_c^2}{k t_{rnhsi}} \tag{11}$$

being t_{rnhsi} the point of intersect between the radial flow and the negative half-slope tangent to the pressure derivative line.

The third characteristic point is seen at late time behavior when steady-state behavior develops. The pressure drop provides a horizontal line. This pressure drop was correlated with several dimensionless aquifer leakage factor as observed in Figure-3. The pressure shows a clearly and strong dependency on leakage factor at which steady state takes place. This is established as given below:

$$b_D = 1.2614 e^{-\frac{kh\Delta P_{ss}}{70.6 q\mu B}} \tag{12}$$

Hence, it is easy to observe that the pressure drop is constant once the steady state is completed reached in a log-log plot of dimensionless pressure drop versus dimensionless time. Nonetheless, to find the steady-state pressure can be used any conventional plot by drawing a horizontal line on the late steady-state period and locating

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the intercept on the *y*-axis. As commented before, this is identified by a flat behavior of either pressure or pressure drop, and then this value is replaced into Equation (12) to simply obtain the leakage factor. It should be remembered that pressure drop is sensitive to skin effect, in contrast to pressure derivative; then, ΔP_{ss} in Equation (12) must be free of skin effects. This means that:

$$\Delta P_{ss} = P_i - P_{wf} - \Delta P_s \tag{13}$$

$$\Delta P_{ss} = P_{ws} - P_{wf} - \Delta P_s \tag{14}$$

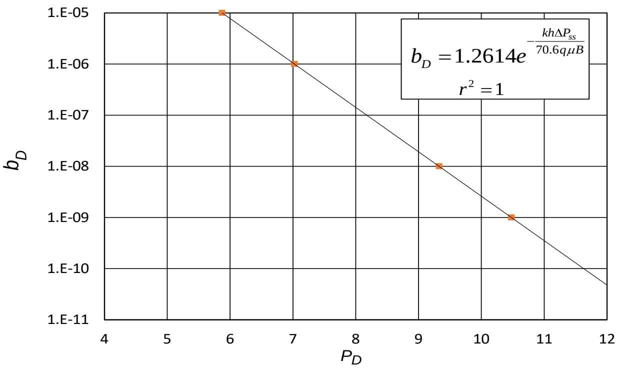

Figure-3. Behavior of the leakage factor as a function of the pressure drop during steady-state period.

Equation (13) and Equation (14) are applied to both drawdown and buildup tests, respectively.

It is recommended to use the equivalent time proposed by Agarwal (1980) in buildup tests.

3. EXAMPLES

3.1 Synthetic Example 1

Cox and Onsager (2002) model was used to develop a simulated test with the below information:

B = 1.00 bbl/STB	q = 820 STB/D
h = 19 ft	μ = 0.73 cp
$L_c = r_w$ = 0.33 ft	c_t = 3.8x10^{-5} psi^{-1}
ϕ = 10 %	k = 692 md
C_D = 0	b_D = 2.8989x10^{-7}
S = 0	

Figure-4 provides pressure, pressure derivative and second pressure derivative versus time for example 1. This test should be interpreted only for the purpose of estimating the leakage factor.

Solution by TDS Technique

The following information was read from Figure-4:

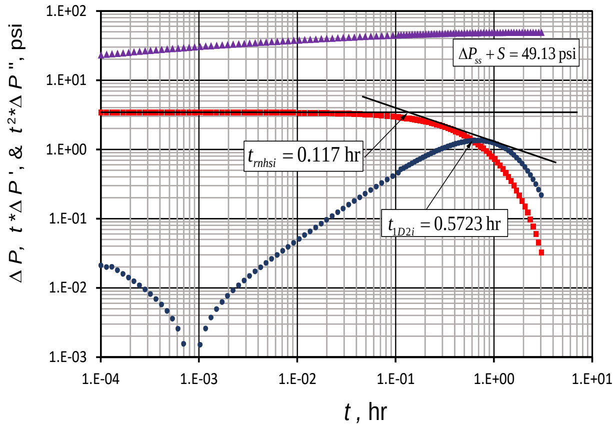

Figure-4. Log-log plot of pressure, pressure derivative and second pressure derivative versus time for example 1.

t_{1D2i} = 0.5723 hr $\quad t_{rnhsi}$ = 0.117 hr $\quad \Delta P_{ss}+S$=49.13 psi

The point of intersection between derivative and second derivative is used to determine leakage factor from Equation (10);

$$b_D = \frac{3583.62(0.1)(0.73)(0.000038)(0.33^2)}{(692)(0.5723)} = 2.7335\times10^{-7}$$

The point of intersection between the radial flow regime and the negative half-slope tangent to the pressure derivative line is also used to find the leakage factor from Equation (11);

$$b_D = \frac{712.5521(0.1)(0.73)(0.000038)(0.33^2)}{(692)(0.5723)} = 2.6586\times10^{-7}$$

Since the pressure drop due to a skin factor of zero is zero. Then, ΔP_{ss}= 49.13 psi which used in Equation (12) will provide:

$$b_D = 1.2614e^{-\frac{(692)(19)(49.13)}{70.6(820)(0.73)(1)}} = 2.9018\times10^{-7}$$

3.2 Synthetic Example 2

Another pressure test was simulated with the below information:

B = 1.00 bbl/STB	q = 1032 STB/D
h = 90 ft	μ = 0.73 cp
$L_c = x_f$ = 30 ft	c_t = 3.8x10^{-5} psi^{-1}
ϕ = 10 %	k = 1200 md
C_D = 0	b_D = 9.7222x10^{-5}
S = 0	

Figure-5 contains a log-log plot of pressure drop, pressure derivative and second pressure derivative versus time. Also find the leakage factor using *TDS* technique.

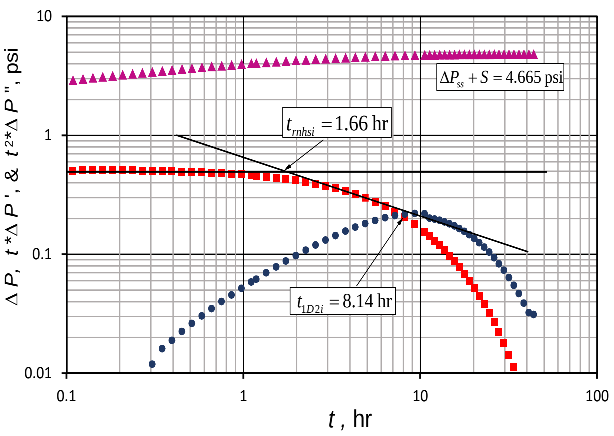

Figure-5. Log-log plot of pressure, pressure derivative and second pressure derivative versus time for example 2.

Solution by TDS Technique

The following information was read from Figure-5:

t_{1D2i} = 8.14 hr t_{rnhsi} = 1.66 hr $\Delta P_{ss}+S$=4.665 psi

Estimate the leakage factor from Equation (10), using the time at which both pressure derivative and second pressure derivative intercept.

$$b_D = \frac{3583.62(0.1)(0.73)(0.000038)(30^2)}{(1200)(8.14)} = 9.1594\times10^{-5}$$

From Equation (11), determine another value of leakage factor with the point of intersection between the radial flow regime line and the negative half-slope tangent to the pressure derivative line;

$$b_D = \frac{712.5521(0.1)(0.73)(0.000038)(30^2)}{(1200)(1.66)} = 8.9305\times10^{-5}$$

The leakage factor is found from the application of Equation (12);

$$b_D = 1.2614e^{-\frac{(1200)(90)(4.665)}{70.6(1032)(0.73)(1)}} = 9.7043\times10^{-5}$$

4. COMMENTS ON THE RESULTS

The results obtained for the determining the leakage factor from the three different ways applying *TDS* technique were excellent; especially those obtained from the Equation (12) which is a correlation between the pressure derivative behavior and leakage factor values when steady state takes place. This could be possible since this expression uses only a natural parameter such as pressure. This allows obtaining absolute deviation errors less than 1%.

Equation (11) which uses the intersect point formed between the radial flow and the negative half-slope tangent to the pressure derivative line (artificially added) provided more accurate results than Equation (10), which comes from the intersect point formed between the two derivatives. It may be due to the facts: (1) includes two artificial parameters, meaning they are estimated not measured, and (2) it is difficult to exactly define such intercept. However, both expressions give results with deviation errors less than 10% in a high-sensitive parameter.

5. CONCLUSIONS

Three new expressions are introduced for determination of the leakage factor from transient pressure analysis using the *TDS* technique. The equations were successfully tested providing errors lower than 1% in the best case.

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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
k	Reservoir permeability, md
L_c	Characteristic length (x_f or r_w), ft
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
s	Laplace parameter
t	Time, hr
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
x_f	Half-fracture length, ft

Greeks

ϕ	Porosity, fraction
μ	Viscosity, cp

Suffices

conf	Confining layer
D	Dimensionless
i	Initial
*1D*2i	Intercept of pressure derivative and second pressure derivative
r	Radial
rnhsi	Intersect of the radial flow line and the negative half-slope tangent to pressure derivate line
ss	Steady state
v, conf	Vertical in confining layer