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# AQUIFER SIZE DETERMINATION FROM MATERIAL BALANCE FOR GAS RESERVOIRS

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## ABSTRACT

During decades, reservoir engineers have used the material balance equation, MBE, for estimating reserves, gas cap size and amount of water influx of oil and gas reservoirs. It has also been used as a tool for prediction the behavior and ultimate recovery of a given hydrocarbon reservoir and, since then, many modifications have been introduced to the MBE. In this work, a reservoir simulation study is conducted for a non-volumetric gas reservoir with different aquifer sizes so a correlation was developed for estimating the size of an underlying aquifer from material balance. The developed expression was successfully tested with field and simulated examples.

**Keywords:** aquifer size, non-volumetric gas reservoir, bottom-water drive.

## 1. INTRODUCTION

Material balance is maybe the most used tool by reservoir engineers during several decades. Its main applications lead to the estimation of hydrocarbon in place, water influx and gas cap size. The general material balance equation was first introduced by Schilthuis (1936). Since then, thousands of papers have been published on either field applications or further developments. With the continuous growing in computer power and mathematical development, the zero dimensional Schilthuis MBE has been replaced for multidimensional mathematical models for simulation a variety of fluid flow situations as indicated by Cheng, Huan, and Ma. G. (2006), among several. However, the Schilthuis MBE, if fully understood and properly used, can provide significant results for the practicing reservoir engineers. Among a great amount of publications on material balance, a method of linearization of the MBE was introduced by Havlena and odeh (1963, 1964) with resulted in a much more practical application of Schilthuis MBE.

The plot of p/Z versus cumulative gas production is a widely accepted method for solving gas material balance under depletion drive conditions. The extrapolation of the plot to atmospheric pressure provides a reliable estimate of the original gas-in-place. If a water drive is present the plot often appears to be linear, but the extrapolation will give an erroneously high value for gas-in-place. The extrapolation of the plot to atmospheric pressure provides a reliable estimate of the original gas-in-place. If a water drive is present the plot often appears to be linear, but the extrapolation will give an erroneously high value for gas-in-place. However, a few years ago, Elahmadi and Wattenberger (2007) recently presented an application of the p/Z plot in water drive gas reservoirs.

The Cole Plot, Cole (1969), is a useful tool for distinguishing between water drive and depletion drive gas reservoirs. The plot is derived from the general material balance equation for gas reservoirs. For oil reservoirs, the Campbell Plot is the counterpart to the Modified Cole Plot for gas reservoirs. The Roach Plot, Poston and Berg (1997), has been presented as a tool for solving the gas material balance in the presence of water drive. Pletcher (200) shows that for water drives that fit the Pot Aquifer model, interpretation can be improved by including water production in the X-axis plotting term. This improves the linearity of the plot and gives more accurate values for OGIP.

Water reservoirs in contact with hydrocarbon reservoirs may be very large or so small that his effect can be neglected. Aquifer activity may be evidenced by water production or low pressure depletion caused by aquifer reaction. However, a few times the aquifer size is known. Since high gas saturation may be trapped from water influx from aquifers, gas recovery factor from no-volumetric reservoirs may be poor (50-70% of OGIP). These recovery factors can be increased by improving the well production. It can also be achieved if the properties of both gas reservoir and aquifer are known. Among them, aquifer size plays an important role in water influx. If the aquifer/gas reservoir radii relationship is greater than 10 the aquifer is considered to be infinite and its water providing capability is higher than finite aquifer size.

Targac, Wattenbarger and Startzman (1990) developed two AIF (aquifer-Influence Function) type curves for aquifers. They were applied to 32 American gas reservoirs; An AIF can be obtained from the production-pressure register of a gas reservoir. The AIF is unique for a given aquifer and, among other applications, can be used for estimation of the aquifer size. The aquifer size can be estimated using the slope, *m*, of a Cartesian plot of AIF vs. Time (months) by using the following expression:

$$V_p = \frac{1}{mc_t} \tag{1}$$

The calculated pore volume corresponds to the pore volume of the aquifer underlying the gas reservoir. The calculation applies to any aquifer geometry only if this acts under pseudosteady state. For infinite aquifer sizes, the aquifer size can be estimated using the late-time slope of the AIF.

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In this work, the estimation of the aquifer size is achieved from a Cartesian plot of $(G_pB_g+W_pB_w)/(B_g-B_{gi})$ vs. $[G+W_e/(B_g-B_{gi})]$. The slope of such plot changes as the aquifer's size changes; then, numerical simulation was used to generate cases for several aquifer sizes then a correlation was established. It was successfully applied to synthetic and field cases. Only the field case is reported.

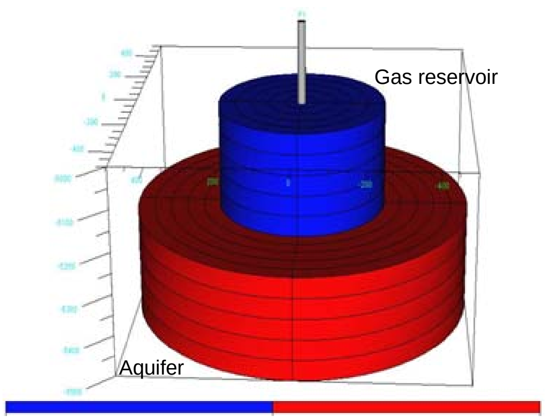


**Figure-1.** Reservoir model with $r_a/r_e$=2.

## 2. SIMULATION SET UP

The study model consists of a conventional dry gas reservoir drained by a unique producer well located in the center of the reservoir. As depicted in Figure-1, there also exists an underlying aquifer is influencing the gas reservoir. A commercial simulator was used to evaluate the gas reservoir behavior under several aquifers' sizes. In this research the gas reservoir volume was kept constant while the aquifer/gas reservoir radii relationship was set to variations ranging from $r_a/r_e$=1, to $r_a/r_e$=10, keeping in mind that relationships higher to 10 corresponds to infinite aquifer size. Since such parameters as permeability have a wide impact in the water influx behavior, Armenta (2003), three different cases were conducted using different permeability values. Besides, the gas flow rate has certain effect on the amount of water influx from the aquifer; then, gas flow rate variations were also consider in the analysis. The three study cases are reported in Table-1.

**Table-1.** Permeability and gas flow rate values considered in the study.

| Case | $q_g$, Mscf/Day | *k*, md |
|---|---|---|
| 1 | 300 | 100 |
| 2 | 400 | 100 |
| 3 | 400 | 500 |

Table-2 and 3 and Figure-2 present the fluid and petrophysical poperties used in the simulation runs. The information data were taking from the work of Armenta (2003) who evaluated the effect of water influx associated to some properties of the reservoir-aquifer system which is similar to this work.

**Table-2.** Fluid and rock properties.

| Parameter | Value |
|---|---|
| $P$, psia | 2500 |
| $P_R$, psia | 1500 |
| $T_R$, °F | 120 |
| $r_e$, ft | 250 |
| $\phi$, % | 25 |
| $B_w$, rb/STB | 1 |
| $c_r$, 1/psia (@ 2500 psia) | $1\times10^{-6}$ |
| $c_w$, 1/psia | $2.6\times10^{-6}$ |
| $\mu_w$, cp | 0.68 |
| $\rho_w$, lbm/ft$^3$ | 64 |
| $\rho_g$, lb/ft$^3$ | 0.046 |

**Table-3.** Viscosity and gas deviation factor.

| *P*, psi | *Z* | $\mu_g$, cp |
|---|---|---|
| 100 | 0.989 | 0.0122 |
| 300 | 0.967 | 0.0124 |
| 500 | 0.947 | 0.0126 |
| 700 | 0.927 | 0.0129 |
| 900 | 0.908 | 0.0133 |
| 1100 | 0.891 | 0.0137 |
| 1300 | 0.876 | 0.0141 |
| 1500 | 0.863 | 0.0146 |
| 1700 | 0.853 | 0.0151 |
| 1900 | 0.845 | 0.0157 |
| 2100 | 0.84 | 0.0163 |
| 2300 | 0.837 | 0.0167 |
| 2500 | 0.837 | 0.0177 |
| 2700 | 0.839 | 0.0184 |
| 3200 | 0.844 | 0.0202 |

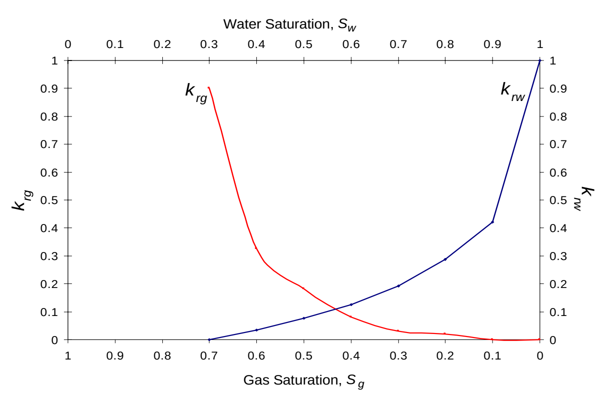


**Figure-2.** Relative permeabilities used in the simulation model.

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The different studied models were simulated using the above input data for a time of 1800 days using a time step of 30 days. It is worth to clarify that for controlling the reservoir during the simulation a gas flow rate of 300 Mscf/Day were used in case 1 and 400 Mscf/Día for cases 2 and 3.

## 3. SIMULATION RESULTS

The simulation runs allowed us to obtain cumulative water produced, $W_p$, cumulative water influx, $W_e$, reservoir pressure, $P_R$, at different time levels, among other important properties. Some results for case 1 are graphically presented here. Results for cases 2 and 3 are very similar.

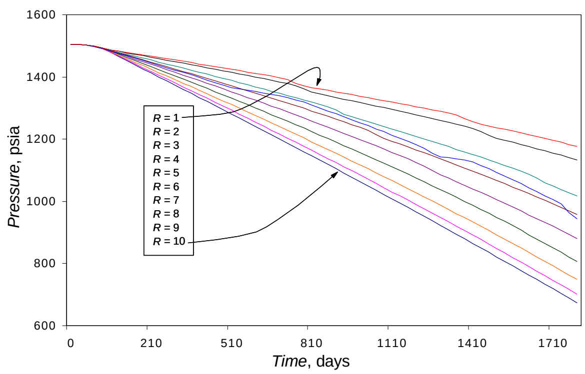


**Figure-3.** Reservoir behavior for case-1.

Figure-3 shows the pressure support given by the aquifer. This becomes stronger as the ratio of the aquifer/reservoir ($r_a/r_e$) radii increases its value. By the same token, Figures 4 and 5 shows that the total amount of cumulative produced water and water influx increases as the ratio of the two geological units also increases. Based upon this observations, it is possible to relate production fluid parameters and reservoir performance with the ratio of the aquifer/reservoir radii (referred here as *R*) by applying the concepts of the material balance equation for non-volumetric gas reservoirs.

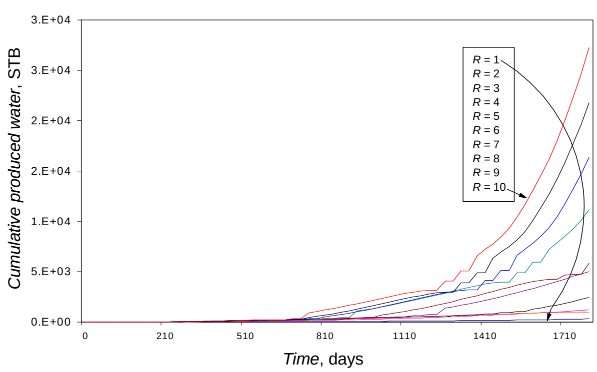


**Figure-4.** Produced water behavior for case-1.

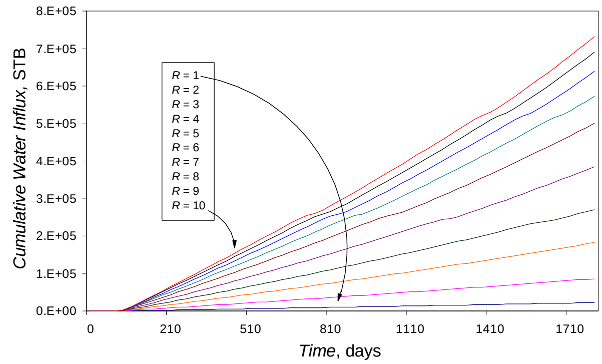


**Figure-5.** Water influx behavior for case-1.

## 4. CORRELATION DEVELOPMENT

Figure-6 shows an application of the method presented by Havlena and Odeh (1963, 1964) for a non-volumetric gas reservoir. The main point is that the water influx has an affect on the angle formed by the plot with an imaginary horizontal line that indicates no water influx. Then, application of the material balance equation was performed with the simulation results (production data) obtained for the above mentioned three cases, the original gas in place (OGIP) and other fluid properties. Figures-7, 8 and 9 show the simulation results for cases 1, 2 and 3, respectively, following the idea expressed in Figure-6.

From simple inspection of the MBE for non-volumetric gas reservoirs, Equation 1, results necessary to normalize the data used in *y* axis of Figure-6 since the original gas in place, *G*, differs from one gas reservoir to other.

$$G+\frac{W_e}{B_g-B_{gi}}=\frac{G_pB_g+W_pB_w}{B_g-B_{gi}} \quad (1)$$

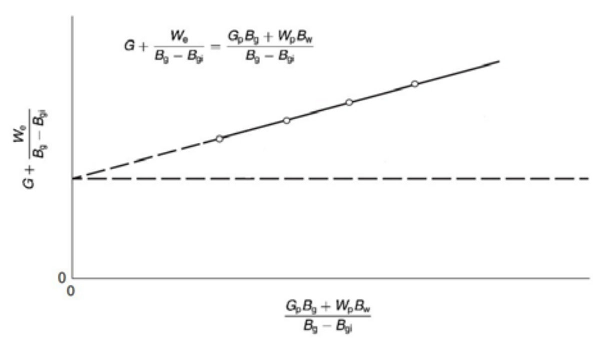


**Figure-6.** Havlena and Odeh's method for non-volumetric gas reservoirs (Ahmed and Mckinney, 2005).

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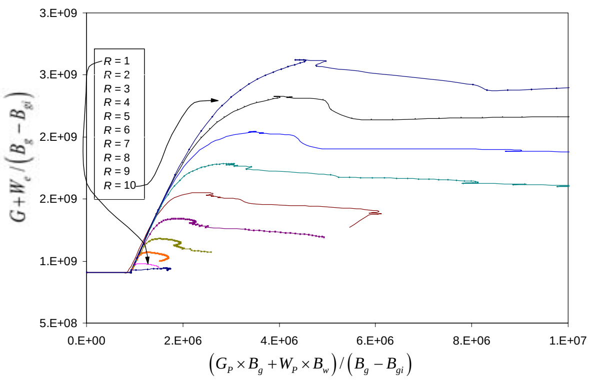


**Figure-7.** MBE application to case-1.

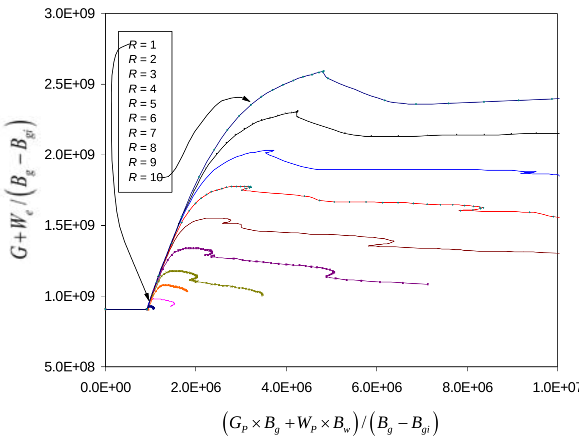


**Figure-8.** MBE application to case-2.

The normalization was performed by dividing by G both sides of Equation 1,

$$1+\frac{W_e}{(B_g-B_{gi})\times G}=\frac{(G_p\times B_g+W_p\times B_w)}{(B_g-B_{gi})\times G} \qquad (2)$$

Equation (2) guaranties that the initial value on the y axis will always be one for any reservoir size.

Figures 7, 8 and 9 allow establishing a remarkable similarity for the different simulated cases for each radii relationship. However, since an adequate tendency for these curves was not found, it was necessary to utilize the maximum points of each curve for each $r_a/r_e$ value, determine their slopes and weight them with the slopes of the other simulated cases as reported in Table-4, so a linear average graphical tendency for each $r_a/r_e$ value is obtained as given in Figure-10.

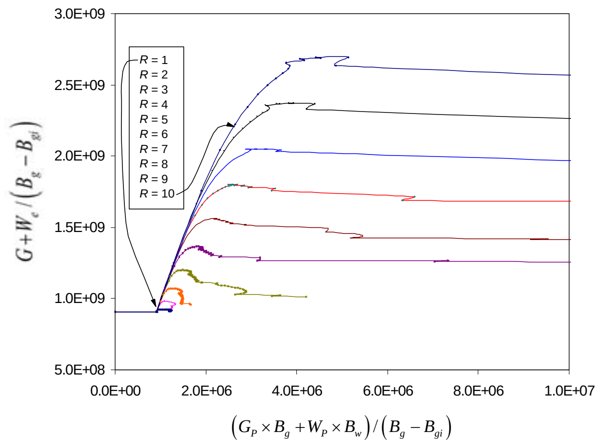


**Figure-9.** MBE application to case-3.

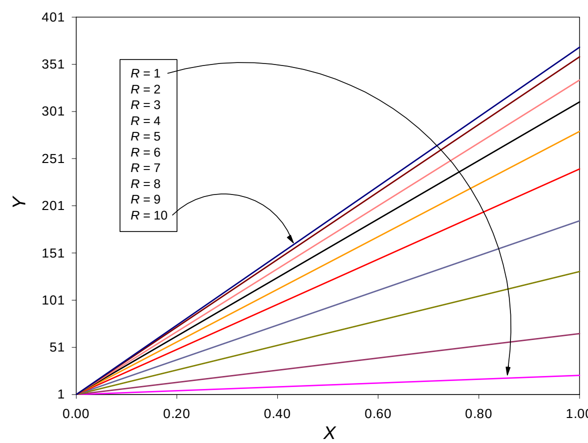


**Figure-10.** Graphical correlation for the determination of $r_a/r_e$.

Finally, with the purpose of organizing the results and becoming Figure-1 into a practical correlation to find $r_a/r_e$ from production data applying MBE, information from Table-4 was used to generate the following expression:

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**Tabla-4.** Maximum points and representative slopes for each $r_a/r_e$ value.

| X | Y | m | $r_a/r_e$ |
|---|---|---|---|
| 0 | 1 | 20.834 | 1 |
| 1 | 21.228.000 | | |
| 0 | 1 | 64.45 | 2 |
| 1 | 65.45 | | |
| 0 | 1 | 130.503 | 3 |
| 1 | 131.503 | | |
| 0 | 1 | 183.896 | 4 |
| 1 | 184.896 | | |
| 0 | 1 | 239.186 | 5 |
| 1 | 240.186 | | |
| 0 | 1 | 278.923 | 6 |
| 1 | 279.923 | | |
| 0 | 1 | 309.966 | 7 |
| 1 | 310.966 | | |
| 0 | 1 | 333.056 | 8 |
| 1 | 334.056 | | |
| 0 | 1 | 357.83 | 9 |
| 1 | 358.83 | | |
| 0 | 1 | 361.94 | 10 |
| 1 | 359.83 | | |

$$\frac{r_a}{r_e} = \exp[0.00612795907595062X - 1.93496367338482\times10^{-5}Y + 0.0053636223223725m + 0.311928640200196] \quad (3)$$

Where

$$X = \frac{(G_p \times B_g + W_p \times B_w)}{(B_g - B_{gi})\times G} \quad (4)$$

$$Y = 1 + \frac{W_e}{(B_g - B_{gi})\times G} \quad (5)$$

The above correlation applies to an isotropic reservoir acting under radial flow conditions with an underlying aquifer. The range of application is given for $5 \le k \le 800$ md, $0.1 \le \phi \le 0.25$, $250 \le r_e \le 3200$ ft. The correlation provides trustable results for finite-size aquifers. For infinite aquifers the correlation allows to infer the infinity condition; however, the radii relationship may not reflect the actual value.

If the aquifer radius were known, the amount of water influx is readily estimated using the van Everdingen and Hurst, Schilthuis or Fetkovich methods, Craft and Hawkins (1991). $W_e$ is an essential parameter needed for the calculations and several times is unknown, it is recommended to use $G$ determined from other source of estimation of in-situ gas reserves. Having this and production data, $W_e$ is estimated from the MBE as follows:

$$W_e = \left(G_p \times B_g + W_p \times B_w\right) - G \times \left(B_g - B_{gi}\right) \quad (6)$$

The above correlation applies to non-volumetric gas reservoirs under the following assumptions: (*i*) isotropic and homogeneous reservoir, (*ii*) radial flow geometry, (*iii*), bottom-drive water influx, (*iv*) IGIP and/or water influx are/is known, and (*v*) fluid production is available.

## 5. FIELD EXAMPLE

Lee and Wattenbarger (1996) present a field example of a dry gas reservoir under the influence of an infinite-active aquifer. The production history and fluid-reservoir information are given, respectively, in Tables-5 and 6.

**Table-5.** Production history for field example.

| *t*, days | $P_R$, psia | $G_p$, Mscf | $W_p$, STB | *Z* | $B_g$, rb/STB |
|---|---|---|---|---|---|
| 0 | 5392 | 0 | 0 | 1.053 | 0.00067815 |
| 182.5 | 5368 | 677.7 | 3 | 1.0516 | 0.00068028 |
| 365 | 5292 | 2952.4 | 762 | 1.047 | 0.00068703 |
| 547.5 | 5245 | 5199.6 | 2054 | 1.0442 | 0.00069133 |
| 730 | 5182 | 7132.8 | 3300 | 1.0404 | 0.00069719 |
| 912.5 | 5147 | 9196.9 | 4644 | 1.0383 | 0.00070052 |
| 1095 | 5110 | 11171.5 | 5945 | 1.036 | 0.00070403 |
| 1277.5 | 5066 | 12999.5 | 7148 | 1.0328 | 0.00070795 |
| 1460 | 5006 | 14769.5 | 8238 | 1.0285 | 0.00071345 |
| 1642.5 | 4994 | 16317 | 9289 | 1.0276 | 0.00071454 |
| 1825 | 4997 | 17868 | 10356 | 1.0278 | 0.00071425 |
| 2007.5 | 4990 | 19416 | 11424 | 1.0273 | 0.0007149 |
| 2190 | 4985 | 21524.8 | 12911 | 1.027 | 0.00071541 |

Water influx was estimated with Equation (4) using the value of original gas in place, $G$ (or OGIP) of $197\text{x}10^6$ Mscf which is reported in the given example. Once $W_e$ is found for each time interval, see Table-7, Figure-11 was built from which the necessary data was taken to be used into Equation (3).

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**Table-6.** Fluid and reservoir data for field example.

| Parameter | Value |
|---|---|
| $\theta$, ° | 360 |
| $h$, ft | 20 |
| $k$, md | 50 |
| $r_e$, ft | 3,383 |
| $\phi$, % | 24 |
| $B_w$, rb/STB | 1 |
| $c_r$, 1/psia | $6x10^{-6}$ |
| $\mu_w$, cp | 1 |

**Table-7.** Estimation of $X$ and $Y$ parameters with the water influx estimated from Equation (3).

| t, days | $W_e$, STB | $Xx10^{-3}$ | $Y$ |
|---|---|---|---|
| 0 | 0 | 0 | 1 |
| 182.5 | 42143 | 0.008262 | 1.10060735 |
| 365 | 280275 | 0.436868 | 1.16025985 |
| 547.5 | 1000217 | 0.79245 | 1.38521796 |
| 730 | 1225629 | 0.881184 | 1.32678167 |
| 912.5 | 2041764 | 1.055609 | 1.46346197 |
| 1095 | 2774188 | 1.167965 | 1.54430182 |
| 1277.5 | 3340842 | 1.219438 | 1.56920967 |
| 1460 | 3592300 | 1.186289 | 1.51663770 |
| 1642.5 | 4500737 | 1.297585 | 1.62792198 |
| 1825 | 5661999 | 1.458224 | 1.79628264 |
| 2007.5 | 6652583 | 1.579954 | 1.91894412 |
| 2190 | 8072502 | 1.761217 | 2.09987560 |

$X$ = 0.000792450
$Y$ = 1.38521796
$m$ = 550.7

Application of the developed correlation, Equation (3), provides a value $r_a/r_e$= 26.1 which corresponds to an infinite-acting aquifer ($r_a/r_e$>10) as stated in the example.

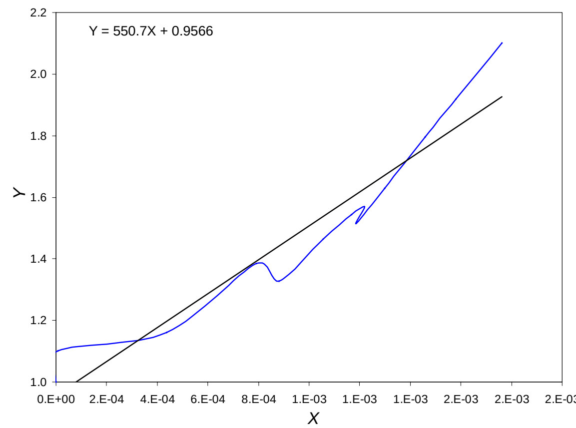


**Figure-11.** Material Balance plot for field example.

## 6. CONCLUSIONS

a) An approximation of the size of an aquifer underlying a gas reservoir is achieved by using numerical simulation considering a constant reservoir size and varying the aquifer size, permeability and gas flow rate. The range of application is given for $5 \leq k \leq 800$ md, $10 \leq \phi \leq 25$ % and $250 \leq r_e \leq 3200$ md. The correlation is applicable if the original gas in place (OGIP), $G$, is known from another source (i.g. volumetric method), so water influx can be estimated. Then, utilizing the material balance equation by means of a normalized Havlena-and-Odeh plot of $[G_pB_g+W_pB_w]/ [(B_g-B_{gi})\ G]$ vs. $[1+W_e/ [(B_g-B_{gi})\ G]\}$, the aquifer size is estimated from the slope of such plot. The correlation was successfully applied to field and synthetic cases.

b) The pressure support from a bottom-drive water influx and the aquifer size on a gas reservoir was reflected in the simulations runs. An increase of aquifer/gas reservoir radii, ra/re, ratio causes higher abandonment pressure.

## ACKNOWLEDGEMENTS

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## Nomenclature

| | |
|---|---|
| $A$ | Reservoir area, Acre |
| $B_w$ | Water volume factor, rb/STB |
| $B_g$ | Gas volume factor, bbl/scf |
| $B_{gi}$ | Initial gas volume factor, bbl/scf |
| $c_t$ | Total compressibility, 1/psia |
| $c_r$ | Rock compressibility, 1/psia |
| $G$ | Original gas in place (OGIP), scf |
| $G_p$ | Cumulative produced gas, scf |

| | |
|---|---|
| $H$ | Reservoir thickness, ft |
| $K$ | Formation permeability, md |
| $M$ | Slope of Cartesian plot |
| $P$ | Reference pressure, psia |
| $P_i$ | Initial reservoir pressure, psia |
| $T_R$ | Reservoir temperature, °F |
| $R$ | $r_a/r_e$ ratio |
| $r_a$ | Aquifer radius, ft |
| $r_e$ | Reservoir radius, ft |
| $V_p$ | Pore volume, rcf |
| $W_e$ | Water influx, STB |
| $W_i$ | Initial water in aquifer, STB |
| $W_p$ | Cumulative produced water, STB |
| $X$ | Parameter defined by Equation (4) |
| $Y$ | Parameter defined by Equation (5) |
| $Z$ | Gas deviation factor |

**Greeks**

| | |
|---|---|
| $\phi$ | Porosity, fraction |
| $\mu$ | Viscosity, cp |
| $\theta$ | Angle |

**Suffices**

| | |
|---|---|
| $g$ | gas |
| $i$ | Initial |
| $r$ | Rock |
| $R$ | Reservoir |

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