

Material Balance Equation (MBE) for Gas-Condensate Reservoirs

By

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Abstract

The phenomenon of retrograde condensation occurs when the reservoir pressure declines below the dew-point pressure causing gas condensation and developing two-phase flow. Material Balance Equation (MBE) of gas condensate reservoirs is a challenge because of the change in fluid composition and complexity of phase behavior. Neglecting the effect of water vaporization may lead to inaccurate predictions of the material balance equation. Therefore, the main objective of this study is to develop an improved MBE model capable of describing gas condensate reservoirs under significant vaporization of connate water and water influx driving mechanism. A new parameter is developed to consider water vaporization. This parameter is used to derive equations for gas condensate reservoirs considering vaporization effect with and without consideration of water influx. Numerical examples have been developed and used to compare the accuracy of the newly-developed model with conventional ones using actual reservoir depletion and production data. The results indicated that water vaporization has an important effect and should be considered for accurate MBE predictions. Error analysis showed that the newly-developed equations are more accurate than previously-developed models. The accuracy of the new MBE is attributed to the additional parameter introduced considering high pressure and high temperature conditions. The application of the new material balance equation will have important impact on predictions of initial gas in place, reserve calculation and future simulation studies.

Key words: gas condensate, material balance, gas predictions, gas reserves.

1. Introduction and Literature Review

Accurate reserve calculation for gas condensate reservoirs is a key component of economic evaluation and decision-making in reservoir development. Gas condensate reservoirs exhibit complex behavior due to the following reasons;

1. A very rapid decrease in gas permeability from 60 to 84% under condensation condition,
2. Variable amount of trapped gas in liquid phase, and
3. Drastic change of residual critical condensate saturation plus a significant drop in formation compressibility³

The technique of material balance equation (MBE) has been widely used in the oil industry for years for reliable reserve estimation. Material-balance equation (MBE) is simply a mass conservation principle used to calculate original gas in place and gas reserves at different stages of reservoir depletion.

The derivation of the MBE is based on the concept of tank model and its application requires accurate data of cumulative fluid production and changes in reservoir pressure. Schilthuis

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³ Zhang M, Ayala LF (2015). A New Material Balance Equation for the Analysis of Liquid Rich Natural Gas Reservoirs. Paper SPE-175081-MS, the SPE Annual Technical Conference and Exhibition, 28–30 September, Houston, Texas, USA.

proposed that cumulative withdrawal of reservoir fluids is equated to the combined effects of reservoir drive mechanisms of fluid expansion, compaction of pore volume and water influx⁴.

Zhang and Ayala³ developed a generalized MBE applicable for liquid-rich gas reservoirs such as wet and retrograde gas reservoirs via a new concept called an equivalent gas molar density. The researchers indicated that using the density based equation does not require the implementation of two-phase z-factors³. The developed-equation did not consider high pressure and high temperature conditions.

Gas-condensate reservoirs are characterized as of rich with molecules of intermediate and heavier hydrocarbon^{5,6}. When reservoir pressure is above the dew-point pressure, gas remains as a single-phase in the reservoir and can be mathematically expressed using material balance equation of a dry gas reservoir as follows:

$$G_T B_{gi} = (G - G_p) B_g \quad (1)$$

Where

- G = original gas in place (scf),
- G_p = cumulative gas produced (scf),
- B_g, B_{gi} = current and initial gas formation volume factors, respectively (rcf/scf),
- G_T = total gas (which includes gas and the gaseous equivalent of the produced condensates) at the initial reservoir pressure above the dew point (scf),

Equation 1 can be re-arranged and expressed in the following convenient form;

$$\frac{p}{z} = \frac{p_i}{z_i} - \frac{p_i}{z_i G} G_p \quad (2)$$

Where

- P and P_i = current and initial reservoir pressures (psia),
- Z and Z_i = single and two phase gas deviation factor (unitless).

The MBE has been popularly applied as a straight-line technique for prediction of future reservoir performance^{7,8}. Using equation 2, a plot of (P/z) versus G_p yields a straight line. This straight line is often used to estimate original gas in place (G) and gas reserve at any abandonment conditions.

When the reservoir pressure decreases below the dew-point pressure, the gas condenses and forms a liquid hydrocarbon phase. Often, a significant volume of this condensate is immobile and remains in the reservoir. Therefore, correct application of material-balance concept requires consideration of liquid volume remaining in the reservoir and also liquids produced at the surface. This condition is mathematically presented in equation 3 considering two gas formation factors (B_{2gi} and B_{2g}) as follows:

³Zhang M, Ayala LF (2015). A New Material Balance Equation for the Analysis of Liquid Rich Natural Gas Reservoirs. Paper SPE-175081-MS, the SPE Annual Technical Conference and Exhibition, 28–30 September, Houston, Texas, USA.

⁴Schilthuis RG (1936). Active Oil and Reservoir Energy. Society of Petroleum Engineers, Transaction of AIME, vol 118, issue 1, December, USA.

⁵Thomas FB, Bennion DB, Andersen G (2009). Gas Condensate Reservoir Performance. Journal of Canadian Petroleum Technology, July, Vol 48, No. 7.

⁶Tiab D (2000). Gas Reservoir Engineering, the University of Oklahoma, School of Petroleum and Geological Engineering, Norman, Oklahoma, USA.

⁷Havlena D, Odeh AS (1963). The Material Balance as an Equation of a Straight Line. Paper SPE 559-PA, vol 18, issue 8, August.

⁸Havlena D, Odeh AS (1964). The Material Balance as an Equation of a Straight Line-Part II, Field Cases. Paper SPE 869-PA, Journal of Petroleum Technology, vol 16, issue 7, July.

$$G_T B_{2gi} = (G_T - G_{pT}) B_{2g} \quad (3)$$

Where

B_{2gi}, B_{2g} = gas formation volume factors at two depletion pressures (rcf/scf),

Equation 3 can be re-written as a function of reservoir pressure and z-factor as below:

$$\frac{p}{z_2} = \frac{p_i}{z_{2i}} - \frac{p_i}{z_{2i}} \frac{G_{pT}}{G_T} \quad (4)$$

Where

Z_2 and Z_{2i} = two-phase gas deviation factors at current and initial conditions (unitless).

Equation 4 suggests that a plot of (P/z_2) versus G_{pT} provides a straight line, which can be used for calculation of the original gas in place and gas reserve.

2. Gas-Condensate Reservoirs with Significant Water Vaporization

The content of equilibrium water vapor increases as the reservoir pressure declines in gas reservoirs. This condition causes vaporization of connate water within the gas-bearing portion of the reservoir. Humphreys stated that in hot and high pressure gas condensate reservoirs, significant vaporization of connate water can occur during depletion⁹. Neglecting this vaporization effect in the general material balance equation is expected to cause erroneous predictions of gas initially in place and hence reserves plus incorrect identification of reservoir drive mechanism.

Humphreys⁹ indicated that no hydrocarbon gas condensation occurs when the reservoir pressure is above the dew-point pressure. However, as the pressure declines, more of the liquid water vaporizes, thus reducing the liquid water saturation as below:

$$\frac{(1 - S_w)(1 - y_w)}{(1 - S_{wi})(1 - y_{wi})} [1 - \bar{c}_f(p_i - p)] \frac{p}{z} = \frac{p_i}{z_i} - \frac{p_i}{z_i} \frac{G_p}{G} \quad (5)$$

Where

C_f = Formation compressibility, psia^{-1}

S_{wi} = irreducible water saturation, fraction

S_w = pore volume water saturation, fraction

S_o = saturation of retrograde condensed liquid in reservoir, fraction

y_w, y_{wi} = mole fractions of water vapor in hydrocarbon phase at current and initial pressures, % mole.

For volumetric reservoirs, equation 5 reveals that a plot of $\frac{(1-S_w)(1-y_w)}{(1-S_{wi})(1-y_{wi})} [1 - \bar{c}_f(p_i - p)] \frac{p}{z}$ versus G_p yields a straight line. At $p/z = 0$ and original gas is equal to cumulatively produced one; such as $G_p = G$. Therefore, the extrapolation of the straight line to $p/z = 0$ provides an estimate of original gas in place.

Assuming that the water saturation remains constant during the life of the reservoir (i.e., $S_w = S_{wi}$ and $y_w = y_{wi}$) and when formation compressibility is assumed negligible, Equation 5 can be reduced to Equation 2 for a volumetric dry-gas reservoir.

When the reservoir pressure decreases below the dew-point pressure, the gas phase condenses. In many gas condensate reservoirs, the liquid hydrocarbons formed in the reservoir remain

⁹ Humphreys NV (1991). The Material Balance Equation for a Gas Condensate Reservoir with Significant Water Vaporization. Paper SPE 21514-MS, the SPE Gas Technology Symposium, Houston, 22-24 January, Houston, Texas, USA.

immobile. Therefore equation 5 is modified to include this additional liquid phase, as shown in equation 6 below⁹.

$$\frac{(1 - S_w - S_o)(1 - y_w)}{(1 - S_{wi})(1 - y_{wi})} [1 - \bar{c}_f(p_i - p)] \frac{p}{z_2} = \frac{p_i}{z_{2i}} - \frac{p_i}{z_{2i} G_T} G_{pT} \quad (6)$$

The form of equation 6 indicates that a plot of $\frac{(1 - S_w - S_o)(1 - y_w)}{(1 - S_{wi})(1 - y_{wi})} [1 - \bar{c}_f(p_i - p)] \frac{p}{z}$ versus G_p provides a straight line of a slope equal to (p_i/z_iG) and an intercept equal to p_i/z_i . At $p/z = 0$, $G = G$. Therefore, an extrapolation of the straight line to $p/z = 0$ provides an estimate of original gas in place.

3. MBE for Gas Condensate Reservoirs Based on Mass Conversion

Another form of material balance equation for gas condensate reservoirs was proposed based on the mass conversion concept¹⁰. They developed a generic form of mass balance equation for natural water driven condensate gas reservoirs under condition of gas injection, as presented below in equation 7.

$$\begin{aligned} \rho_{gi}GB_{gi} - (\rho_{gsc}G_p + \rho_{osc}N_p) \\ = \left\{ \left[1 - \frac{(\bar{C}_f + C_w S_{wi})\Delta p}{1 - S_{wi}} \right] GB_{gi} - (W_e - W_p B_w) - G_{ip} B_{gdr} \right\} [\rho_g(1 - S_o) + \rho_o S_o] \end{aligned} \quad (7)$$

In case of no-edge water and no bottom water, equation 7 will be as below:

$$\rho_{gsc}G_p + \rho_{osc}N_p = \rho_{gi}GB_{gi} - \left[1 - \frac{(\bar{C}_f + C_w S_{wi})\Delta p}{1 - S_{wi}} \right] GB_{gi} [\rho_g(1 - S_o) + \rho_o S_o] \quad (8)$$

Assuming that $Y = \rho_{gsc}G_p + \rho_{osc}N_p$ and $X = B_{gi}\{\rho_{gi} - [1 - \frac{(\bar{C}_f + C_w S_{wi})\Delta p}{1 - S_{wi}}][\rho_g(1 - S_o) + \rho_o S_o]\}$, equation 8 can be presented in a straight line form of $Y = GX$. A plot of Y vs. X results in a straight line with a slope equal to the original gas in place.

If there is no water influx or gas injection, equation 8 can be reduced to the following equation:

$$\rho_{gi} - \frac{\rho_{gsc}G_p}{GB_{gi}} = \left[1 - \frac{(\bar{C}_f + C_w S_{wi})\Delta p}{1 - S_{wi}} \right] \quad (9)$$

Considering density in terms of equation of state, equation 9 will be:

$$\frac{p_i}{z_i} \left(1 - \frac{G_p}{G} \right) = \frac{p}{z} \left[1 - \frac{(\bar{C}_f + C_w S_{wi})\Delta p}{1 - S_{wi}} \right] \quad (10)$$

Equation 10 is the form of mass balanced equation for seal dry gas reservoir. A small modification of equation 10 is made by using 2-phase gas factor. This is presented in equation 11 below.

$$\frac{p_i}{z_{2i}} \left(1 - \frac{G_p}{G} \right) = \frac{p}{z_2} \left[1 - \frac{(\bar{C}_f + C_w S_{wi})\Delta p}{1 - S_{wi}} \right] \quad (11)$$

¹⁰ Luo Z, Wang N, Liu P, Li N, Liu F (2013). A New Form of Material Balance Equation of Condensate Gas Reservoir. Journal of Chemical and Pharmaceutical Research, 5(12):1440-1445.

This study assumed that the usage of the two-phase gas deviation factor in equation 10 provides a model for gas condensate reservoir based on the mass balance¹⁰. This model is given above by equation 11.

4. Derivation of an Improved Material Balance Equation

Considering a volumetric gas condensate reservoir at initial conditions, the following parameters are defined as follows:

$$VPPV_i = PV_i(1 - S_{wi}) \quad (12)$$

$$VPPV_i = HVPV_i \times \frac{1}{(1 - y_i)} \quad (13)$$

$$VPPV_i = G_i B_{gi} \times \frac{1}{(1 - y_i)} \quad (14)$$

$$PV_i = \frac{G_i B_{gi}}{(1 - y_i)(1 - S_{wi})} \quad (15)$$

Where

PV = pore volume

VPPV = vapor phase pore volume,

HVPV = hydrocarbon vapor phase pore volume

At some depleted pressure, above the dew-point, the formation and connate water compressibility are given by;

$$\bar{C}_f = \frac{-1}{PV_i} \times \frac{\Delta PV}{\Delta P} \quad (16)$$

$$C_w = \frac{-1}{WV_i} \times \frac{\Delta WV}{\Delta P} \quad (17)$$

$$C_w = \frac{-1}{(S_{wi} \times PV_i)} \times \frac{\Delta WV}{\Delta P} \quad (18)$$

Change on pore volume at some depleted pressure with water influx is defined below:

$$PV = PV_i + \Delta PV + \Delta VW - W_e \quad (19)$$

$$PV = PV_i + (-\bar{C}_f \times PV_i \times \Delta P) + (-C_w \times S_{wi} \times PV_i \times \Delta P) - W_e \quad (20)$$

$$PV = PV_i(1 - \Delta P(\bar{C}_f + C_w S_{wi})) - W_e \quad (21)$$

$$A = 1 - \Delta P(\bar{C}_f + C_w S_{wi}) \quad (22)$$

Parameter A combines formation and water compressibility's plus pressure drop.

$$PV = PV_i(A) - W_e \quad (23)$$

$$PV = \frac{G_i B_{gi}}{(1 - y_i)(1 - S_{wi})}(A) - W_e \quad (24)$$

Vapor phase pore volume at some depleted pressure is defined by equation 25 as follows:

$$VPPV = PV(1 - S_w) \quad (25)$$

Defining the hydrocarbon phase in terms of gas remaining in the reservoir gas (G):

$$VPPV = \frac{GB_g}{(1 - y)} \quad (26)$$

Combining equations (23) and (25) provides:

$$PV = \frac{VPPV}{(1 - S_w)} = \frac{GB_g}{(1 - y)(1 - S_w)} = \frac{G_i B_{gi}}{(1 - y_i)(1 - S_{wi})} (A) - W_e \quad (27)$$

Equation 27 is the material balance equation above the dew point pressure for a gas condensate reservoir with significant water vaporization considering formation and water compressibility plus water influx.

Defining G_P as the cumulative hydrocarbon gas production and applying a material balance on the hydrocarbon gas provides;

$$G = G_i - G_P \quad (28)$$

$$\frac{(G_i - G_P)B_g}{(1 - y)(1 - S_w)} = \frac{G_i B_{gi}}{(1 - y_i)(1 - S_{wi})} (A) - W_e \quad (29)$$

$$\frac{G_i \times B_g}{(1 - y)(1 - S_w)} - \frac{G_P \times B_g}{(1 - y)(1 - S_w)} = \frac{G_i B_{gi}}{(1 - y_i)(1 - S_{wi})} (A) - W_e \quad (30)$$

Defining a new parameter M to consider change in proportion of water in hydrocarbon phase with water saturation (S_w) and gas formation factor is given by:

$$M = \frac{B_g}{(1 - y)(1 - S_w)} \quad (31)$$

$$M_i = \frac{B_{gi}}{(1 - y_i)(1 - S_{wi})} \quad (32)$$

$$G_i M - G_P M = G_i M_i A - W_e \quad (33)$$

$$G_P = G_i \left(1 - \frac{M_i}{M} A \right) + \frac{W_e}{M} \quad (34)$$

Equation 34 is the material balance equation above the dew point pressure for a gas reservoir with significant water vaporization considering formation and water compressibility plus water influx, where B_g is the single-phase gas formation volume factor.

At some depleted pressure, below the dew-point pressure, the following equation is developed:

$$G_P = G_i \left(1 - \frac{M_{HCL_i}}{M_{HCL}} A \right) + \frac{W_e}{M_{HCL}} \quad (35)$$

Where;

$$M_{HCL_i} = \frac{B_{2gi}}{(1 - y_i)(1 - S_w - S_{HCL_i})} \quad (36)$$

$$M_{HCL} = \frac{B_{2g}}{(1 - y)(1 - S_w - S_{HCL})} \quad (37)$$

Where M is the gas formation volume factor at certain values of water saturation S_w and water phase mole fraction. At some depleted pressure below the dew-point pressure, the presence of liquid condensate at pore space with a fraction of S_{HCL} makes this term become M_{HCL} to consider the portion of pore space occupied by liquid condensate.

Equation 35 is a newly-developed material balance taking into consideration the effect of connate water vaporization represented by the term M_{HCL} . Also, the effect of water influx is described by $\{\frac{W_e}{M_{HCL}}\}$. Applying equation 35 reveals that a plot of G_P vs $(1 - \frac{M_{HCLi}}{M_{HCL}})A$ results in a straight line with a slope equal to initial gas in place and an intercept of $\frac{W_e}{M_{HCL}}$.

Rearranging equation 35 to be expressed as below

$$\left(1 - \frac{M_{HCLi}}{M_{HCL}}\right) \frac{G_i}{G_P} + \frac{W_e}{M_{HCL}G_P} = 1.0 \quad (38)$$

Equation 38 can be simplified as below

$$GZEDI + WDI = 1.0 \quad (39)$$

Where

$GZEDI$ = gas zone expansion drive index

WDI = and water influx drive index.

5. Applications of Current and Newly-Developed Material Balance Equations

Actual field data of an over-pressured gas condensate reservoir was presented by Humphreys⁹ and used for verification of the new equation and comparison of results attained from current MBEs. Four calculation solved examples are presented as follows:

Case 1: MBE for volumetric gas condensate reservoir without water influx

Case 2: MBE for volumetric gas condensate reservoir with water influx

Case 3: New MBE for volumetric gas condensate reservoir without water influx

Case 4: New MBE for volumetric gas condensate reservoir with water influx

Table 1 presents the PVT fluid data while Table 2 lists production data in cumulative recovery of original gas in place. This actual data indicates a high temperature of the reservoir at 350 °F.

The production data of cumulative gas produced, and corresponding average reservoir pressure is presented in Table 2.

Case 1: Volumetric Gas Condensate Reservoir without Water Influx

Using the data listed in Table 3 and applying the MBE of equation 3 is described below.

Reforming equation 3 taking into consideration no water influx yields;

$$\frac{G_P}{G_i} = \left(1 - \frac{B_{2gi}}{B_{2g}}\right) \quad (40)$$

Equation 40 is a straight-line equation passing through the origin and has a slope equal to initial gas in place G . A graphical plot of cumulative production (column 1) versus change in gas formation factors (column 4) using data of Table 2 is presented in Figure 1. Setting the intercept to the origin, the slope of the plot will result in unity.

Results presented in **Figure 1** show an over estimate of about 28.4% since the calculated value is 1.285 for the slope.

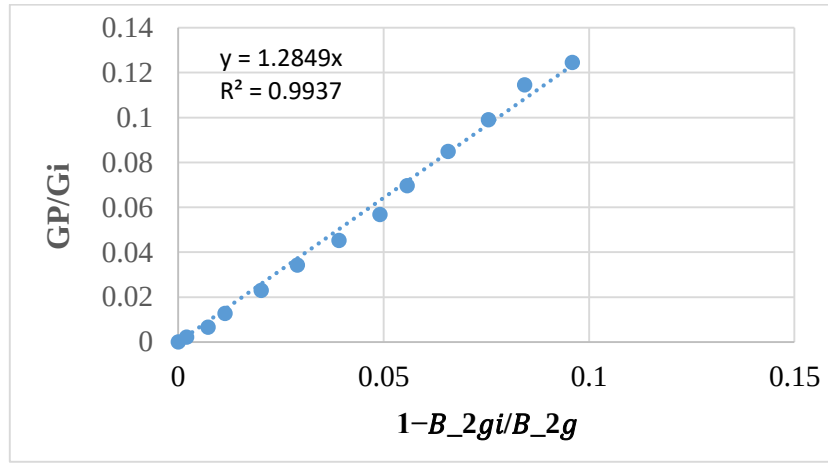


Figure 1. MBE of a volumetric gas condensate reservoir without water influx.

Case 2: MBE for Volumetric Gas Condensate Reservoir with Water Influx

Reforming equation 40 and considering water influx effect provides the following equation:

$$\frac{G_P}{G_i} = \left(1 - \frac{B_{2gi}}{B_{2g}}\right) + \frac{W_e}{B_{2g} \times G_i} \quad (41)$$

A graphical plot of equation 41 as a straight line indicates that the slope is unity and the intercept is equal to $\left\{\frac{W_e}{B_{2g} \times G_i}\right\}$. Calculations for application of equation 41 are the same as in the previous case of gas condensate reservoir, equation 3, but the fit line is not set to the origin.

Results presented in **Figure 2** showing, again, an over estimate of 33.3% since the slope is 1.333. However the negative omitted value of the intercept indicating the error in this assumption.

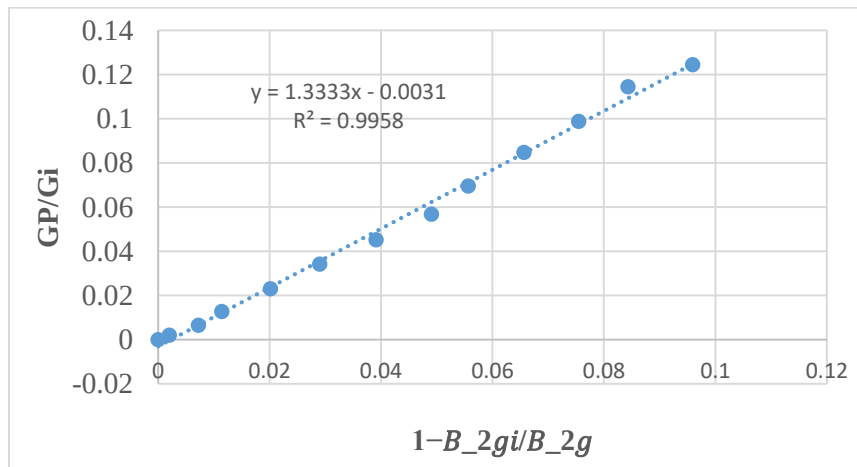


Figure 2. MBE of a volumetric gas condensate reservoir with water influx.

Case 3: New MBE for Gas Condensate Reservoir without Water Influx

The newly developed material balance equation which considers the vaporization of connate water is presented in equation 35. Reforming equation 35 to eliminate the water influx effect will result in the following equation;

$$\frac{G_P}{G_i} = \left(1 - \frac{M_{HCL_i}}{M_{HCL}} A\right) \quad (42)$$

A new parameter is developed as M in equation 42. This parameter M was not involved in previous equation considering water vaporization of condensate reservoirs. This equation is different from equation 5 because equation 5 didn't consider the change in water compressibility in pore space which has a considerable effect. The effect of water and formation compressibility is described in parameter A. Calculations of this case are presented in the following Table 4.

Setting the intercept to the origin will result in an over estimate of about 0.24% as shown in Figure 3.

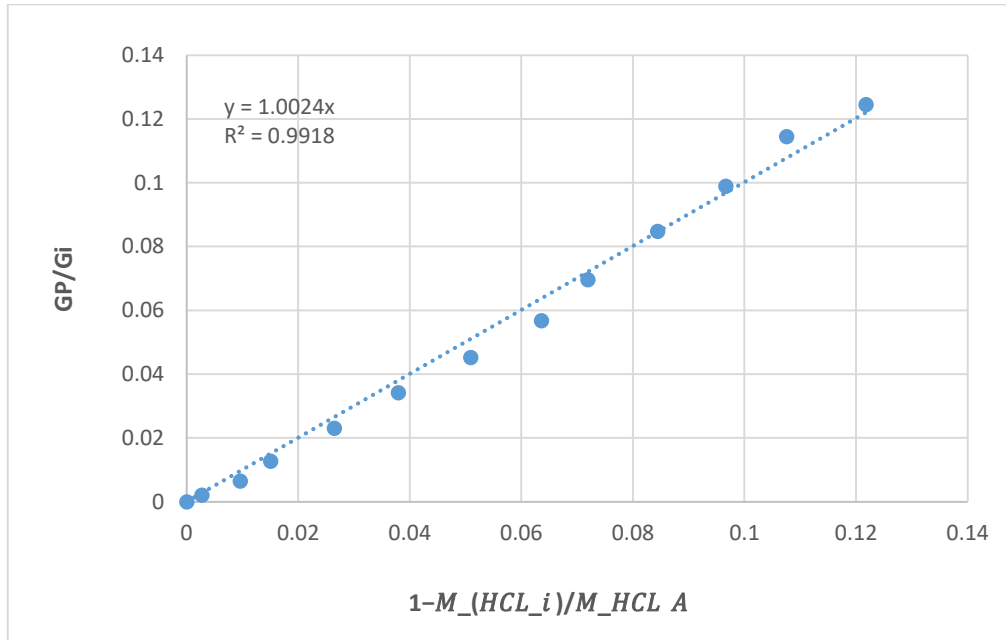


Figure 2: Newly developed MBE without water influx effect.

Case 4: New MBE for Gas Condensate Reservoir with Water Influx

Starting from equation 35 and taking into consideration water vaporization and water influx. Calculations are the same as in case 3 of gas condensate reservoir without water influx but the fit line is not set to the origin.

The MBE as a straight line of **Figure 4** has a slope of 1.047. A calculated value of the error of 4.7 % is attributed to the presence of water influx of the reservoir. The intercept value is considered to be neglected verifying case 3 which assume no water influx.

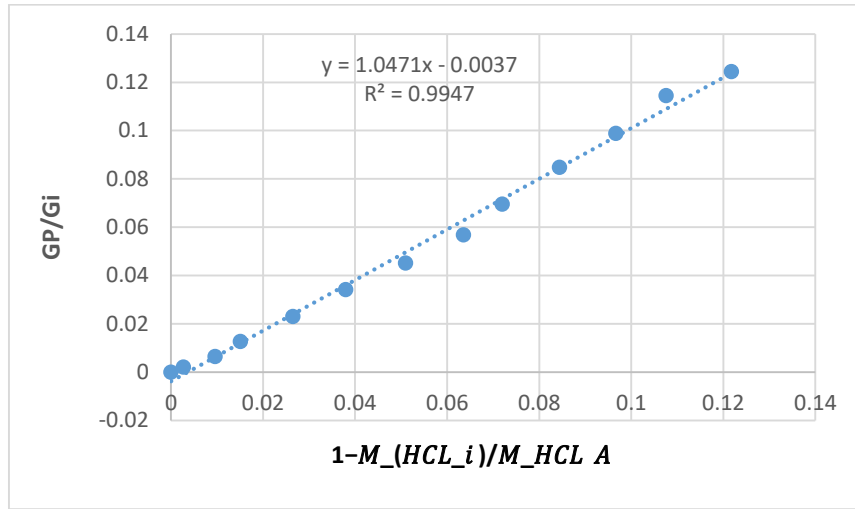


Figure 3: Newly developed MBE for gas condensate reservoir with water influx.

5. Conclusions

This study presents an improved material balance equation (MBE) for gas condensate reservoirs with consideration of the effects water vaporization and water influx. A statistical error analysis is carried out and the following conclusions are attained:

1. Conventional materials balance equations for gas condensate reservoirs with and without effect of water influx have been evaluated and applied using actual field data.
2. Two new material balance equations have been developed for gas condensate reservoirs with consideration of significant water vaporization and water influx.
3. Application of the newly-developed equations indicates more accuracy for predicting the initial gas condensate in place than the conventional models.
4. A statistical error analysis of all material balance equations for gas condensate reservoirs is carried out and indicates that conventional equation without water vaporization and water influx has the biggest error while the newly developed ones showed the lowest.

Nomenclature

B_{gi}	Initial formation volume factor of gas, RB/scf
B_o	Formation volume factor of condensate, RB/STB
B_w	Formation volume factor of water, RB/STB
B_{gdr}	Formation volume factor of injection gas, RB/scf
C_f	Formation compressibility, $psia^{-1}$
C_w	Compressibility coefficient of water, $psia^{-1}$
G	Original gas in place, scf
G_p	Cumulative gas produced, scf
G_T	Total gas, which includes gas and the gaseous equivalent of the produced condensates, at the initial reservoir pressure above the dewpoint, scf
G_{pT}	Cumulative gas produced including gas and equivalent condensate produced at the surface, scf
G_{ip}	Accumulate injection of gas, scf
GZEDI	Gas Zone Expansion Drive Index
N_p	Cumulative production of oil condensate, STB
P	Current reservoir pressure, psia
P_i	Initial reservoir pressure, psia
S_w	Pore volume water saturation, fraction

S_o	Saturation of retrograde condensed liquid in reservoir, fraction
S_{wi}	Irreducible water saturation, fraction
WDI	Water Influx Drive Index
W_e	Water influx in gas reservoir, RB
W_p	Accumulate production of water, STB
y_w, y_{wi}	Mole fractions of water vapor in hydrocarbon phase at current and initial pressures, % mole.
y_w	Mole fraction of water vapor in hydrocarbon phase, %mole
Z	Single phase gas deviation factor, unitless
Z_i	Single phase gas deviation factor at initial conditions, unitless
Z_2	Two phase gas deviation factor, unitless
Z_{2i}	Two phase gas deviation factor at initial conditions, unitless

Symbols

ρ	Density, lb/ft ³
ρ_{gi}	Initial density of gas at formation condition, lb/ft ³
ρ_{gsc}	Density of gas at ground standard condition, lb/ft ³
ρ_{osc}	Density of condensate oil at ground standard condition, lb/ft ³
ρ_g	Density of gas at present formation condition, lb/ft ³
ρ_o	Density of condensate oil at present formation condition, lb/ft ³

Table 1. PVT fluid data of gas reservoir.

Initial water vapor	4.1 mole %
Initial Inert gases (CO ₂ + N ₂)	14.5 mole %
Dew point pressure	4500 psia
Reservoir temperature	350 °F
Initial reservoir pressure	7100 psia
Initial gas molecular weight	26.1

Pressure psia	Vapor Phase z-factor	Mole % Water (Vapor Phase)	Volume % Water (Liquid Phase)	Volume % Hydrocarbon (Liquid Phase)
7000	1.104	4.1	9.97	0
6000	1.036	4.47	9.94	0
5000	0.974	4.97	9.89	0
4500	0.946	5.31	9.86	Trace
4000	0.927	5.67	9.82	0.3
3000	0.908	6.81	9.72	1.12
2000	0.911	9.08	9.54	1.4
1000	0.934	15.95	9.14	1.37
200	0.955	70.22	6.98	1.2

Table 2. Production Data

Net Cumulative Gas Produced % GIIP	Average Reservoir Pressure, psia
0	7115
0.21	7088
0.65	7020
1.27	6966
2.3	6855
3.42	6745
4.52	6622
5.68	6504
6.96	6427
8.48	6313
9.89	6203
11.45	6106
12.45	5981

Table 3. Volumetric material balance calculations.

Net Cumulative Gas Produced % GIIP	Average Reservoir Pressure, psia	B_g, rb/scf	$(1 - \frac{B_{2gi}}{B_{2g}})$
0	7115	0.000642	0
0.21	7088	0.000643	0.002047
0.65	7020	0.000647	0.007251
1.27	6966	0.000649	0.011435
2.3	6855	0.000655	0.020176
3.42	6745	0.000661	0.029028
4.52	6622	0.000668	0.039154
5.68	6504	0.000675	0.049095
6.96	6427	0.00068	0.055704
8.48	6313	0.000687	0.065668
9.89	6203	0.000694	0.075485
11.45	6106	0.000701	0.08431
12.45	5981	0.00071	0.095918

Table 4. Newly developed material balance calculations.

Net Cumulative Gas Produced % GIIP	Average Reservoir Pressure, PSIA	Bg, RB/scf	A	M	$\left(1 - \frac{M_{HCLi}}{M_{HCL}} A\right)$
0	7115	0.000642	1	0.000748	0
0.21	7088	0.000643	0.999377	0.00075	0.002709351
0.65	7020	0.000647	0.997807	0.000754	0.009573833
1.27	6966	0.000649	0.996561	0.000757	0.015066823
2.3	6855	0.000655	0.993999	0.000764	0.026474297
3.42	6745	0.000661	0.99146	0.000771	0.037933633
4.52	6622	0.000668	0.98862	0.000779	0.050929832
5.68	6504	0.000675	0.985895	0.000788	0.063579126
6.96	6427	0.00068	0.984117	0.000793	0.071929178
8.48	6313	0.000687	0.981485	0.000802	0.08443066
9.89	6203	0.000694	0.978944	0.000811	0.096650888
11.45	6106	0.000701	0.976704	0.000819	0.107555148
12.45	5981	0.00071	0.973816	0.00083	0.121784168

Comparison of different cases of MBEs and error analysis is presented in Table 5. This analysis indicates that the application of modified MBE of dry gas reservoir for gas condensate reservoir with water influx provides the biggest error (33.3 %) while the newly developed MBE for gas condensate reservoir without water influx develops the smallest error of 0.2 %.

Table 5. Comparison of calculated G and resultant error.

MBE Case	Calculated G, scf	Error (%)
Case 1: Gas condensate reservoir with no water influx, equation 40	1.284	28.4
Case 2: Gas condensate reservoir with water influx, equation 41	1.333	33.3
Case 3: New gas condensate reservoir with no water influx, equation 42	1.002	0.2
Case 4: New Gas condensate reservoir with water influx, equation 35	1.047	4.7