



Improved gas resource calculation using modified material balance for overpressure gas reservoirs



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ABSTRACT

The p/z plot of an overpressure gas reservoir with a closed boundary typically is a downward concave curve. Overestimation of the original gas in place (OGIP) caused by incorrect extrapolation of the early production data is often observed in reserve evaluation. To eliminate this error, a comprehensive compressibility term that includes pore volume compressibility, water compressibility, and gas solubility in water has been introduced into the p/z plot. To achieve the above objective, it is critical to obtain the right average reservoir pressure corresponding to the drained gas reserve at the time of interest. But for overpressure gas reservoirs, if we completely ignore the permeability changes as the reservoir pressure declines, the reservoir performance will not be representative. Another substantial deficiency of the conventional method is that the solution gas in connate water has been neglected in estimating the OGIP. As a result, the contribution of solution gas to the total gas production is omitted in the material balance equation (MBE). These missing terms lead to an inaccurate estimation of the OGIP and gas reserve. Considering that the permeability is not constant throughout the reservoir life, but a function of pressure, rock and fluid properties, production volume, and original pore volume, we present a new form of MBE which includes the effects of the permeability change due to pore volume change and the contribution of solution gas in connate water to the total gas production. With the proposed semi-analytical equations, the average reservoir pressure and reservoir deliverability can be more accurately estimated. Therefore, the evaluations of OGIP and recoverable gas are more reliable.

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1. Introduction

The term “overpressure” has been commonly used to refer to high pressure, super-normal pressure or surpressure reservoirs. Technically, the overpressure is the amount of pore pressure in excess of the normal one in overpressured formations. Overpressure can result from a number of conditions, which include: (1) Abnormally high pore pressure related to geostatic load; (2) Abnormally high pore pressure related to the density contrast between reservoir fluid (if oil or gas) and interstitial water. Usually, the pressure gradient of an overpressure gas reservoir is higher than 0.5 psi/ft and can be as high as 0.9 psi/ft. Overpressure gas reservoirs with a closed boundary typically have p/z vs. G_p plots with a concave downward shape. Overestimation of the OGIP induced by extrapolating the early production data is often observed in reserve evaluation. To eliminate this error, a

comprehensive term that includes pore compressibility, water compressibility, and gas solubility in connate water has been introduced into the p/z plot so that the correct OGIP can be achieved.

Many studies have been focused on the overpressure gas reservoirs. Timko and Fertl (1971) studied the relationship between hydrocarbon and geopressure, and addressed the economic significance of geopressure reservoirs. Hammerlindl (1971) predicted the gas reserve in abnormally pressured reservoirs using the p/z vs. G_p plot. The rock and water compressibility effects were included to calibrate the plot; thus, an accurate OGIP and reserve could be obtained. Ramagost and Farshad (1981) included the formation compressibility into the p/z term and obtained a straight line in the plot for abnormally pressured gas reservoirs. Roach (1981) adapted the MBE for geopressure gas reservoirs by adding total compressibility to p/z . The modified plot $(p/z)c_t$ vs. G_p is a straight line. Poston and Chen (1987) determined formation compressibility and gas in place in abnormally pressured reservoirs simultaneously using material balance. Prasad and Rogers (1987) studied an overpressure gas

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reservoir in the Gulf Coast using a generalized tank model. In their model, the effective compressibility was used. Ireland and Robinson (1987) predicted the reserve in geopressure gas reservoirs with production testing data. Fertl and Leach (1988) investigated the impacts of reservoir pressure, temperature, formation and fluid properties, and abandonment pressure on the economics of hydrocarbon reserve. Poston and Chen (1989) studied geopressure reservoirs in South Louisiana and South Texas. In their study, numerical simulation was employed to solve the MBE of Ramagost and Farshad (1981). Elsharkawy (1995) used both analytical and numerical solutions of material balance equations to estimate gas in place for abnormal pressure reservoirs. Elsharkawy (1996) proposed a new MBE that includes water influx for overpressure gas reservoirs. Fetkovich et al. (1998) derived a general MBE for high pressure gas reservoir. Gan et al. (2001) developed a semi-analytical p/z technique for the analysis of reservoir performance of abnormally pressured gas reservoirs. Their method required trial-and-error to solve for the OGIP. Oscar et al. (2004) used the material balance of Fetkovich et al. (1998) to diagnose the production mechanisms of gas reservoirs. Sun et al. (2007) evaluated the productivity and performance of stress-sensitive overpressure gas reservoirs. Gonzales et al. (2008) developed an approximation relationship for the MBE of abnormally pressured gas reservoirs. Akande and Spivey (2012) investigated pore volume stress effects in overpressure shale gas. Their studies showed that the in-situ stress reduced the pore volume, thus leading to a lower permeability.

Past peer researches showed that the right average reservoir pressure was the key parameter in developing the MBE. However, for the overpressure gas reservoir, the average reservoir pressure obtained from reservoir performance is not representative if we ignore the rock property changes, such as permeability and porosity, induced by pressure decline. Another deficiency of the conventional method is that the solution gas in connate water is neglected in estimating the OGIP.

Although previous researches on the overpressure reservoir are extensive, to the best of our knowledge, none of them has considered all of such missing parameters as solution of gas in connate water and permeability deterioration in reserve estimation. Our research shows that these missing parameters have significant impact on production forecast and reserve booking.

2. The modified material balance equation for overpressure gas reservoirs

The classical general material balance equation states that the production volume can be equated with the volume change in the reservoir. Expressing the net production on the left-hand-side and volume change on the right-hand-side, the general MBE (Schilthuis, 1936) is

$$\begin{aligned} N_p [B_t + (R_p - R_{soi})B_g] - G_i B_g + W_p B_w - W_i B_w &= N(B_t - B_{ti}) + mNB_{ti} \left(\frac{B_g}{B_{gi}} - 1 \right) \\ &+ \frac{(1+m)NB_{ti}(c_f + c_w S_{wc})}{1 - S_{wc}} (p_i - p) + W_e \end{aligned} \quad (1)$$

where

$$\begin{aligned} m &= GB_{gi}/NB_{oi} \\ B_{ti} &= B_{oi} \\ B_t &= B_o + (R_{soi} - R_{so})B_g \end{aligned}$$

A review of Equation (1) shows that the general MBE neglects the solution of natural gas in brine. In a real situation, hydrocarbon dissolves in irreducible water in both oil leg and gas cap. In overpressure gas reservoirs, the amount of solution gas in brine can be significant. Therefore, incorporating the gas solution in brine in Equation (1), we have

$$\begin{aligned} N_p [B_t + (R_p - R_{soi})B_g] - G_i B_g + W_p B_w - W_i B_w &= N(B_t - B_{ti}) \\ &+ mNB_{ti} \left(\frac{B_g}{B_{gi}} - 1 \right) + V_{bulk} \phi \{ S_{wc} R_{swi} - [1 + c_w(p_i - p)] S_{wc} R_{sw} \} B_g \\ &+ \frac{(1+m)NB_{ti}(c_f + c_w S_{wc})}{1 - S_{wc}} (p_i - p) + W_e \end{aligned} \quad (2)$$

In Equation (2), $V_{bulk} \phi \{ S_{wc} R_{swi} - [1 + c_w(p_i - p)] S_{wc} R_{sw} \} B_g$ is the gas volume evolving out of brine as reservoir pressure declines from initial pressure, p_i , to current pressure, p (Appendix A). The term $[1 + c_w(p_i - p)] S_{wc}$ represents the unit water volume at the current pressure. R_{sw} is the brine gas solubility at the current pressure. Considering the fact that the majority composition of natural gas is methane, the solubility of natural gas in salt water can be approximately estimated by empirical correlations of methane solubility. McCain (1990) recommended correlations to calculate the natural gas solubility (Appendix B).

The general MBE can be adapted to overpressure gas reservoirs with a closed boundary. The following assumptions are made to derive the gas production as a function of producing time:

- 1) No liquid dropout of the gas in the reservoir condition.
- 2) Single-phase flows during the life of the reservoir. Water is an immobile phase.
- 3) The reservoir is homogeneous.
- 4) The reservoir is occupied by gas and irreducible water.
- 5) No gas is injected into the reservoir.
- 6) Reservoir temperature is constant.

With the above assumptions, Equation (2) can be written as follows:

$$\begin{aligned} GB_{gi} \left(\frac{B_g}{B_{gi}} - 1 \right) + W_e - W_p B_w &+ \frac{GB_{gi}}{1 - S_{wc}} (c_f + c_w S_{wc} - B_g c_w S_{wc} R_{sw}) (p_i - p) \\ &+ \frac{GB_{gi}}{1 - S_{wc}} S_{wc} (R_{swi} - R_{sw}) B_g = G_p B_g. \end{aligned} \quad (3)$$

Dividing both sides of Equation (3) by the traditionally defined term, A ,

$$A = N_p [B_t + (R_p - R_{soi})B_g] = G_p B_g, \quad (4)$$

we obtain

$$\begin{aligned} \frac{GB_{gi} \left(\frac{B_g}{B_{gi}} - 1 \right)}{A} + \frac{W_e - W_p B_w}{A} &+ \frac{\frac{GB_{gi}}{1 - S_{wc}} (c_f + c_w S_{wc} - B_g c_w S_{wc} R_{sw}) (p_i - p)}{A} \\ &+ \frac{\frac{GB_{gi}}{1 - S_{wc}} S_{wc} (R_{swi} - R_{sw}) B_g}{A} = 1. \end{aligned} \quad (5)$$

Equation (5) can be abbreviated and expressed for gas reservoirs as

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