Production Analysis Method Based on Material Balance Pseudo-time for Water Production Gas Wells

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Abstract. Material balance pseudo-time has the characteristics of both pseudo-time and material balance time; it can not only realize the linearization of gas flow equation, but also establish equivalent relation of gas wells between variable rate and constant rate, it becomes one of the most important parameters in modern production analysis. In addition, due to the complicated mechanism of gas and water flow and the difficulty in describing the gas and water relationship, the production analysis method for the water production gas well is still in the exploratory stage, and there is no effective method which is widely adopted. Therefore, this paper starts from the material balance equation of gas-water reservoir, builds the expression of material balance pseudo-time, and acquires water content in gas reservoir by the use of production index curves method. In further, it is possible to calculate permeability (K), drainage radius (Re), gas well reserve (G), and so on. Consequently, a production analysis method which provides effective guidance for water production gas wells is built.

Keywords: Material balance pseudo-time · Water production gas well · Gas-water reservoir · Production analysis

Nomenclatures

B_w	Formation volume factor of water [m³/m³]
C_{ti}	Total system compressibility at initial reservoir pressure [1/MPa]
C_{gi}	Gas compressibility at initial reservoir pressure [1/MPa]
G	Original gas in place [10^8m³]
G_p	Cumulative gas production [10^4m³]
p_i	Initial reservoir pressure [MPa]
p	Currently reservoir pressure [MPa]
p_{sc}	0.101[MPa]
p_p	Pseudo-pressure at currently reservoir pressure [MPa²/(mPa s)]
q_g	Production rate [10^4m³/d]
T	Reservoir temperature [K]

T_{sc} 293.15 [K]
t_a Material balance pseudo-time[d]
W Water volume in gas reservoir [$10^8 m^3$]
W_p Cumulative water production [$10^4 m^3$]
Z_i Gas compressibility factor at initial reservoir pressure
Z Gas compressibility factor at currently reservoir pressure
$\overline{C}_t$ Total system compressibility at average reservoir pressure [1/MPa]
μ_{gi} Gas viscosity at initial reservoir pressure [mPa s]
$\overline{\mu_g}$ Gas viscosity at average reservoir pressure [mPa s]

1   Introduction

At present, the widely used pseudo-time in production analysis is based on pure gas wells; it does not apply to water production gas wells.

Because of producing water, pure gas flow in reservoir gradually becomes gas-water flow that greatly reduces gas relative permeability. Gas and water flow together may cause a water-blocking effect which will lead to gas seepage channels blocked and reduce effective porosity of the gas formation [1]. For these above, gas productivity will be decreased greatly. At this time, the inflow performance relationship is totally different with pure gas well, and the relationship between production and bottom hole pressure will no longer be the same with pure gas drive reservoir, but gas-water reservoir which considers not only gas production and pressure changes but also gas well water rate. Then on the basis of gas-water reservoir model, one will acquire the new method for computing pseudo-time for water production gas wells.

Nowadays, the main research results on material balance pseudo-time are presented as follows: Based on gas drive reservoir, Blasingame introduced pseudo-time into production analysis [2], from then on, pseudo-time was used in almost all of the production analysis methods. Afterward, N. M. Anisur Rahman revised this method and proposed a pseudo-time computation method for real gas [3]. Then D. M. Anderson and L. Matter developed a method to calculate pseudo-time for transient flow which considered characteristics of different flowing stages [4]. Further, Shahab Gerami et al. proposed a new way for nature fracture gas reservoir [5]. However, all these methods above are normal methods [6], and it has been demonstrated that they are just applied to pure gas wells but not apply to water production gas wells [7]. These methods could not solve problems in production analysis for water production gas wells.

In this paper, a new method for computing pseudo-time for water production gas wells is presented. This method is based on gas-water reservoir material balance equation that considers transient water influx, water production rate, and water PVT properties.

2 Gas-water Reservoir Material Balance Equation

According to gas reservoir classification by drive type [8], there are pure gas drive reservoir and water drive gas reservoir. The latter one can be further classified into edge-water reservoir and bottom-water reservoir by connection types of gas and water boundary, they are traditional water drive reservoir. While in this study, it is realized that there is the third type of water drive reservoir which is defined as gas-water reservoir.

This kind of reservoir is normally tight gas and has very gentle structure. During the process of hydrocarbon accumulation, its gas-water separation is not completely done and water preserves in formation as isolated lenticel water, gas and water layer overlap in profile. For these reasons, usually, there is no clearly gas and water boundary in gas-water reservoir. So it cannot be classified into either edge-water or bottom-water reservoir; thus, it is the third type of water drive reservoir. There is a typical gas-water reservoir in the northwest of china, the west part of Sulige gas field (Fig. 1).
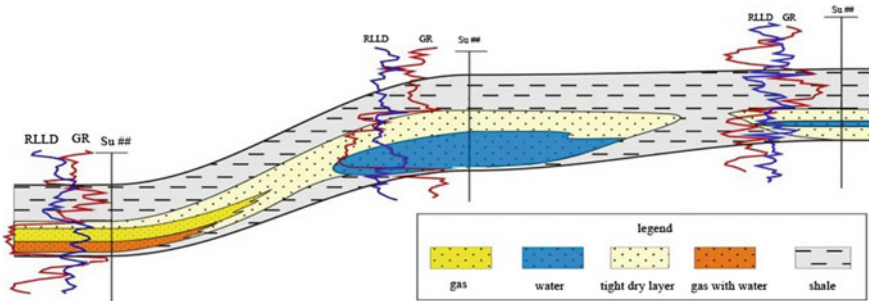

Fig. 1. Gas-water reservoir stratigraphic section in the west of Sulige gas field: this is the lenticel water isolated by tight dry layer

Comparing with traditional water drive reservoir, gas-water reservoir has much smaller water volume and is hard to happen mass water invasion, its well produced water all comes from the lentical water itself without any surrounding supplement. Therefore, it is realized that the main characteristics of gas-water reservoir are the following three points:

- There is no clearly gas and water boundary, gas and water layer overlap in profile.
- Most formation water is isolated lenticel water or the water in the bottom of the structure.
- The scale of the water is small and the connectivity of the water is poor each other.

Based on the three points, it is possible to deduce gas-water reservoir material balance equation. When reservoir pressure drop is Δp, the main volume changes of the reservoir are the following four parts:

- Cumulative gas production and cumulative water production $(G_pB_g + W_pB_w)$;
- Expansion volume of gas in the reservoir: $(GB_g - GB_{gi})$;
- The volume reduction of pore with gas that caused by expansion of immobile water and reduction of reservoir pore: $\left(GB_{gi}\left(\frac{C_wS_{wi} + c_p}{1 - S_{wi}}\right)\Delta p\right)$
- Transient water influx $(W(p))$; Among them, the last one $(W(p))$ is associated with bottom hole pressure and working rules of gas well. The variation of transient water influx has three stages. In the early time of production, for the pressure drawdown has not come to gas-water transition zone, the well products without water, $W(p)$ equals zero; after that, pressure drawdown comes to gas-water transition zone, formation water flows to wellbore through high-permeability zone from every direction, gas well begins to product a large number of water, $W(p)$ increases rapidly; at last, when pressure drawdown gradually becomes steady, $W(p)$ maintains a certain level and water production keeps steady or get down slowly.

In conclusion, gas-water reservoir material balance equation can be presented as Eq. (1)

$$GB_g - GB_{gi} + GB_{gi}\left(\frac{C_wS_{wi} + c_p}{1 - S_{wi}}\right)\Delta p + W(p) = G_pB_g + W_pB_w \tag{1}$$

For a normal pressure reservoir, the equation can be simplified into:

$$G\left(1 - \frac{p/z}{p_i/z_i}\right) = G_p - (W(p) - W_pB_w)\frac{pT_{sc}}{p_{sc}zT}. \tag{2}$$

3   Pseudo-time for Water Production Gas Wells

Pseudo-time is an equivalent time which is derived from material balance equation, and it makes analysis modeling more accurate through bringing in pseudo-pressure and considering PVT changes of fluid during production. In addition, pseudo time makes different production manners in constant pressure or production have the same analysis curves [9]. Therefore, gas well production manners will have no interference to rate transient analysis. For these advantages, most of the modern production analysis methods take use of pseudo-time, such as Blasingame, Agarwal-Garder [10], and normalized pressure integral [11]. Based on the gas-water reservoir material balance equation, it is possible to acquire pseudo-time formulation for water production gas wells. Firstly, take the derivative of Eq. (2) with respect to time, one will get Eq. (3), where p/Z is the function of time.

$$-\frac{G}{p_i/Z_i}\frac{\partial}{\partial t}\left(\frac{p}{z}\right) = q_g - \left(W(p) - W_p B_w\right)\frac{T_{sc}}{p_{sc}T}\frac{\partial}{\partial t}\left(\frac{p}{z}\right) \tag{3}$$

$$C_g = \frac{1}{p/z}\frac{\partial}{\partial p}\left(\frac{p}{z}\right) \tag{4}$$

Then combining with Eq. (4) [12], Eq. (3) becomes

$$q_g = C_g\frac{p}{z}\left[\left(W(p) - W_p B_w\right)\frac{T_{sc}}{p_{sc}T} - \frac{G}{p_i/z_i}\right]\frac{\partial p}{\partial t} \tag{5}$$

$$t_a = \frac{\mu_i c_{ti}}{q}\int_0^t \frac{q}{\bar{\mu}\bar{C}_t}dt \tag{6}$$

For gas reservoir, it is known that $C_g \approx C_t$, then substituting Eqs. (5) into (6), it follows Eq. (7)

$$t_a = \frac{\mu_{gi} c_{ti}}{q_g}\left[\left(W(p) - W_p B_w\right)\frac{T_{sc}}{P_{sc}T} - \frac{G}{p_i/Z_i}\right]\int_{p_i}^p \frac{p}{\mu_g z}dp \tag{7}$$

Combining the definition of pseudo-pressure Eq. (8) [13], finally, pseudo-time for water production gas wells is expressed as Eq. (9):

$$P_p = 2\int_{p_i}^p \frac{p}{\mu_g z}dp \tag{8}$$

$$t_a = \frac{\mu_{gi}C_{ti}\left(P_{pi} - P_p\right)}{2q_g}\left[\frac{G}{p_i/z_i} - \left(W(p) - W_p B_w\right)\frac{T_{sc}}{p_{sc}T}\right] \tag{9}$$

4   Computation of Transient Water Influx

In Eq. (9), the transient water influx changes with formation pressure drawdown and variations of gas product rate. In this paper, water influx will be calculated by the method of production index curves [14]. This method considers that both pure gas drive reservoir and water drive reservoir have the same linear characteristic in initial part of pressure drawdown curves ($p/Z - G_p$), that is because gas production has not been affected by water influx. Afterward, with increasing of water influx, pure gas drive reservoir and water drive reservoir become different. It is realized that the difference ($\Delta(p/z)$) between the extension of the initial line in pressure drawdown curve is obviously caused by water influx (Fig. 2). Based on this theory, one will get the
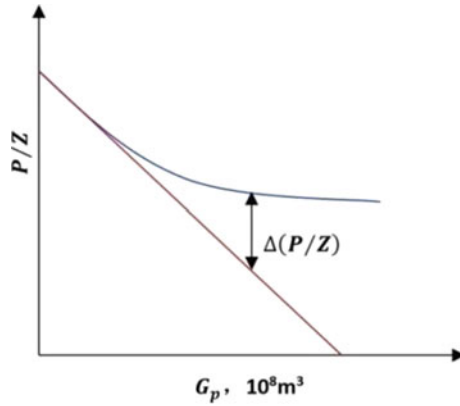
Fig. 2. Pressure drawdown curves for pure gas drive reservoir (the red line) and water drive gas reservoir (the blue line)

formulation for calculating volume of transient water influx in gas-water reservoir. There is another expression for gas-water reservoir material balance equation as

$$\frac{p}{z} = \frac{p_i}{z_i} \left(\frac{1 - G_p/G}{1 - \omega} \right) \tag{10}$$

where

$$\omega = \frac{W(p) - W_p B_w}{G} \tag{11}$$

Or expresses as

$$\frac{p}{z}(1 - \omega) = \frac{p_i}{z_i}\left(1 - G_p/G\right) \tag{12}$$

The corresponding form of material balance equation for gas drive reservoir is Eq. (13)

$$\frac{p}{z} = \frac{p_i}{z_i}\left(1 - G_p/G\right) \tag{13}$$

Combining with Eqs. (12) and (13), one gets

$$\Delta(p/z) = \omega \cdot \frac{p}{z} \tag{14}$$

So

$$\omega = \Delta(p/z) \cdot \frac{p}{z} \qquad (15)$$

Thus, integrating Eqs. (11) and (15), one gets Eq. (16) which is the formulation for calculating transient water influx in gas-water reservoir.

$$W = W_p B_w + G B_{gi} \cdot \Delta(p/z) \cdot z/p \qquad (16)$$

This new method makes calculating of transient water influx simplified greatly, it is allowed one to acquire transient water influx only by gas well production data, and there is no more need to evaluate water shape and size through a series of complicated computation. The accuracy of this method is closely associated with production data which is in accordance with production analysis; therefore, errors will have no propagation and growth in the process of calculating transient water influx and the following production analysis.

5   Results

Combining Eqs. 2, 9 and 16, it is possible to calculate material balance pseudo-time of water production gas wells and then plot Blasingame type curves for production analysis. More than 50 water production gas wells in Sulige gas field are selected to calculate pseudo-time by use of the normal method and the new method, respectively.
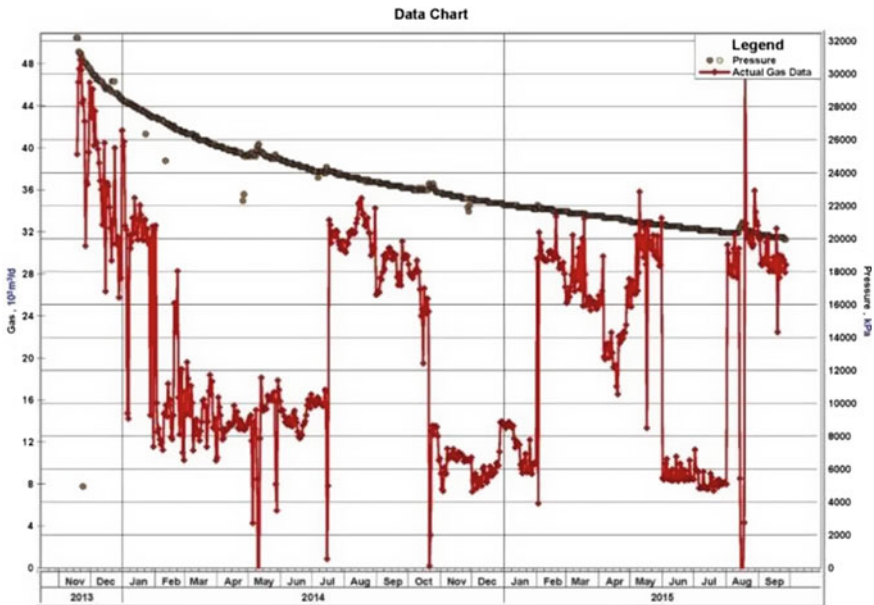

Fig. 3. Production rate versus time for Su#3

Through a large number of calculations, it is found that the new method obviously reduces production data divergence and fluctuation and improves their fitting rate.

Su#3 is a water production gas well which has produced for 679 days, its average water–gas ratio is 2.52 m^3/10^4 m^{3,} and cumulative production is 2000 × 10^4 m^3. Its production data is very scattered (Fig. 3). The reason is that water production makes relationship of gas production and bottom hole pressure changed and leads to normal method no longer apply to water production gas wells. Therefore, it is necessary to take use of the new method to adapt water production wells. SU#3 Blasingame curves by the new method and normal method are shown in Figs. 4 and 5 and the result is shown in Table 1.
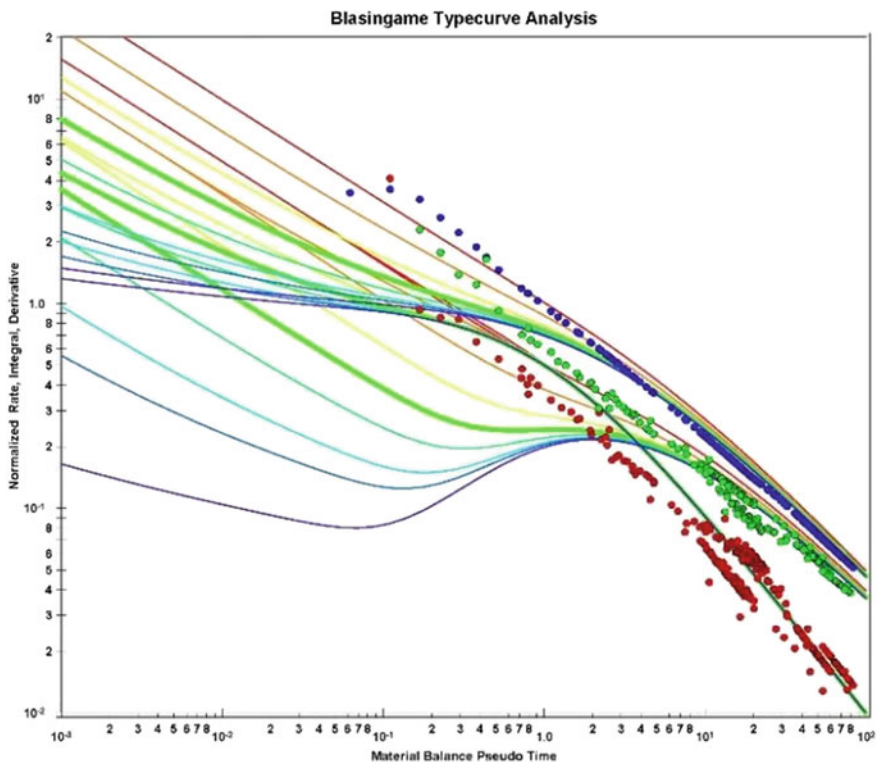

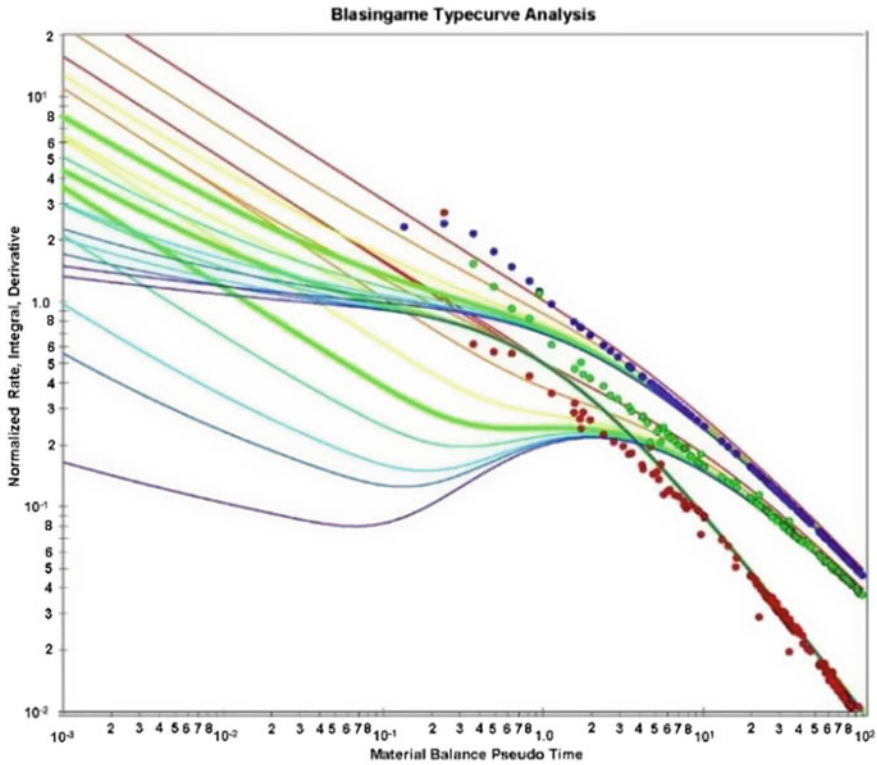**Fig. 4.** Blasingame plot by normal method for Su#3

Fig. 5. Blasingame plot by new method for Su#3

Table 1. Production analysis result for Su#3

Permeability (K)	Fracture half-length (Xf)	Drainage radius (Re)	Reserve (G)
0.23 mD	109.6 m	497 m	4854.5×10^4 m^3

6   Conclusions

This study presents the following conclusions:

- Gas-water reservoir is the third type of water drive reservoir, this paper states its balance relationship between gas and water and presents material balance equation for it.
- Based on gas-water reservoir material balance equation, this paper constructs a new method for computing material balance pseudo-time for water production gas wells.
- The new method provides a potent theoretical support for production analysis of water production gas wells and makes water production analysis more accurate.

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