Research of Dynamic Reserves Estimation Methods for Complex Gas Wells in Low Permeability and Tight Gas Reservoir

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Abstract. As material basis of compiling and adjusting developing scheme, dynamic reserves are crucial for predicting well spacing density and stable production potential. Currently, for conventional gas wells with good physical properties and abundant pressure test data, the main evaluation methods of dynamic reserves are ranging from material balance equation to flowing material balance. However, complex gas wells in Ordos Basin such as type of inadequate pressure test data in low permeability reservoir, water production, downhole throttling in tight gas reservoir, these three types of wells cannot be easily applied to the current evaluation methods. Therefore, this paper presents rapid methods for estimating dynamic reserves in complicated situations which are based on analysis of gas wells percolation and production. The key points of new methods are evaluation of the formation pressure without shutting well, visual pressure drop and water influx, pseudo-pressure regularization rate under superposition time function respectively. Finally, with applying methods to track and evaluate the dynamic reserves of M gas field in Ordos Basin, results show that approaches are accurate and evaluation periods are greatly shortened. Besides, the procedures are simple which can be implemented in desktop application or spreadsheet with minimal computational effort. The new methods provide a direct reference for the deployment of gas infilling wells and gas wells refracturing, and further improve the utilization level of reserves.

1. Introduction

As material basis of gas reservoir, dynamic reserves refer to the OGIP involved in percolation, which are comprehensively reflect the dynamic characteristics of gas reservoirs and related to the formulation and adjustment of gas field development plans [1]. Recently, for conventional gas wells features as good reservoir physical quality and abundant field pressure test data, material balance equation, elastic two phases method and flowing material balance equation are commonly used methods for evaluating dynamic reserves [2][3][4][5]. Among of them, material balance equation is the most frequently used due to its high accuracy and ease of application.

However, the permeability of reservoirs in Ordos Basin are generally low and tight. Usually typical characteristics can be summarized as long time period of pressure recovery, diverse production characteristics, big quantity difference in pressure test data and large number of wells. In fact, the number of conventional gas wells accounts only for 7.2% of the total gas wells, which means current
evaluation methods of dynamic reserves are difficult to apply to those residual complex gas wells such as lack of pressure data in low permeability reservoir, water production and downhole throttling in tight reservoir.

Changqing gas area in Ordos basin locates in the hub position of China's gas supply network. And it is responsible for the arduous task of industry and living gas supply to 18 large cities and regions including Beijing, Tianjin, North China, Central China and East China. Therefore, according to characteristics of percolation and developing features of low permeability and tight gas reservoir in Changqing gas area, it is necessary to use regular dynamic monitoring data (with a little/without depending on field pressure test data) to find out the robust dynamic reserves evaluation methods of complex gas wells with accuracy and efficiency.

2. Difficulties
From the geological background aspect, the Ordos Basin is a large sedimentary basin with multiple tectonic systems, multi-cycle evolution and multi-sedimentary types. It develops gas bearing series in vertical, which are described as weathering crust carbonate reservoirs in Lower Paleozoic Ordovician and tight sandstone reservoir in Upper Paleozoic Permian. Affected by reservoir physical properties, water production characteristics and development modes, the adaptability of dynamic reserves appraising methods for different types of gas well are various.

The typical representative Lower Paleozoic carbonate reservoir is Jingbian gas field. Compared with conventional high/medium permeability gas reservoirs, well pressure recovery is slow (pressure recovery time is usually 3~5 months) [6][7]. There is great contradiction between the pressure measurement and demand for gas supply, which is leading to limited field pressure test data. Thus, traditional methods based on pressure testing such as material balance equation cannot be applied comprehensively. Moreover, Some Lower Palaeozoic carbonate reservoirs are affected by both structure and physical properties. When the gas reservoir fluid produces, pressure difference is generated between the gas reservoir and the surrounding water body. Then water body invades through the original interface, and the gas well begins to produce water. The problems for this count two aspects. The first one, considering water invasion, the external pressure recharge is obtained at the bottom of the well from water body, so that the curve of material balance equation turns to deflection upward. Dynamic reserves cannot be deduced from the straight line section. Second aspects is related to classic water invasion models such as Schilthuis, van Everdingen, Fetkovich [8][9][10]. All of above require uncertain forms and properties of water bodies, or complex computation, which are mean not ease of application.

The typical Upper Paleozoic Sandstone Reservoir represented by Sulige gas field is tight, heterogeneous, and muddy interlayer developed, and its percolation ability is worse than Lower Palaeozoic reservoirs. There are two difficulties in evaluating the dynamic reserves of such gas reservoirs. To begin with, tight reservoir leads to gas well entering into pseudo steady state for quite long time, and the well-controlled dynamic reserves and discharge area are varying with the producing time. Secondly, different from the high pressure development model of lower permeability gas reservoir, the upper paleo gas reservoir adopt downhole throttle production model in order to save the investment and prevent formation of water [11][12], which cannot be frequently extracted throttle to measure the pressure in the production process. In short, the existing dynamic reserves evaluation methods are difficult to qualified for time variability and deficiency of pressure test data.

3. Methods
Due to evaluating difficulties above, on the basis of analysing the percolation laws of different types of gas reservoirs and the production characteristics of gas wells, the evaluation technology of inadequate pressure test data in low permeability reservoir, water production, downhole throttling in tight gas reservoir are proposed in this paper prospectively.
3.1. Type of inadequate pressure test data in low permeability reservoir

For the type of lack of pressure data in low permeability reservoir, a new method for calculating field pressure without shut in wells is put forward. According to relationship between the tested pressure gradient of the well bore and the wellhead pressure, the regression equation of the pressure gradient of the wellbore and the wellhead pressure is established under the condition of closing the well. Then field pressure under the different wellhead pressure can be calculated.

The calculation model of filed pressure is shown as (1).

\[ p = p_a + D \times H \]  

(1)

By using the relationship chart of the pressure gradient of the wellbore and the pressure of the wellhead (500 meters), the regression relationship (figure 1) under the condition of closing the well is established.

\[ D = 0.000074p_a + 0.000085 \]  

(2)

Figure 1. Wellbore pressure gradient vs. wellhead pressure.

As a result, the field pressure under different wellhead pressure can be obtained by substituting (2) in (1) since known wellhead pressure. This method can calculate the single well pressure through a large number of gas wells production data, make up for the shortcomings of the inadequate test data and the cumbersome process, and finally meet the quantitative needs of the whole gas field pressure evaluation. Case study in M gas field shows that the evaluation ratio of material balance equation method increase 43% during 2012~2017, which is relying on this new method to replenish pressure data into the curve of material balance equation (in the figure 2, blue points are calculating pressure data). Results also show that the contradiction between shut in pressure measurement and gas well continuous production in the gas field is relieved.

3.2. Type of Water production

For the type of water production gas wells, after study on characteristics of water production in typical blocks, a "visual pressure difference method", which is not dependent on the shape and property of water body, is established to evaluate the dynamic reserves of these gas wells. Based on the material balance principle of water drive gas reservoir [13] (figure 3), the method quantitatively describes the production characteristics before and after the water invasion of gas reservoirs (in the figure 4, the red curve reflects the production characteristics of the gas reservoir under water influx, while the blue line indicates the production characteristics of the seal gas reservoir.). The vertical distance between two curves (visual pressure difference ), which is resulted by the red curve upward deflection, is size of water invasion. Finally, model of water invasion volume coefficient and water influx under different producing time is established, and the dynamic reserves of gas well are repeatedly corrected by water influx.
Figure 3. Material balance equation with water influx.

Figure 4. P/Z vs cumulative gas production in water influx gas reservoir.

The first procedure is defining the volume coefficient of water influx by the material balance principle of water drive as (3).

$$\omega = \frac{W_e - W_p B_w}{GB_{gi}}$$  \hspace{1cm} (3)

Water influx can be obtained as (4).

$$W_e = GB_{gi} \cdot \omega + W_p B_w$$  \hspace{1cm} (4)

For water production gas reservoirs, when considering it as the normal pressure system and neglecting the expansion of the bound water and the expansion of the rock compression, the equation of material balance can be written as (5).

$$\frac{p}{Z} = \frac{p_i}{Z_i} \left( \frac{G - G_p}{G - (W_e - W_p B_w) \frac{p T_i}{Z_i p_w T}} \right)$$

(5)

The volume coefficient of water influx is introduced into the equation (5), then subtracting the material balance equation from seal gas reservoir. The visual pressure difference can be written as (6).

$$\Delta P_p = \omega p / Z$$

(6)

When do computation, a water invasion coefficient can be computed by calculating every visual pressure difference by using (6). Then let dynamic reserves extrapolated from curve of material balance equation to (4), and the water influx We at this time is obtained. At last, the dynamic reserves after water influx can be corrected repeatedly by substitution (5). This method can quickly predict the dynamic reserves of early water invasion only with producing data and a small amount of pressure test data. In addition, the dynamic reserves of the gas wells in the other blocks of the gas field without pressure test data can be calculated by the dynamic reserves ratio statistics of typical gas wells under water production (the value from visual pressure difference estimation) and non-water-production (the value from curve of material balance equation extrapolated as seal gas reservoir) situation.

### 3.3. Type of downhole throttling in tight gas reservoir

For type of downhole throttling gas wells in tight gas reservoirs (the proportion of gas wells in the gas area is over 70%), an analytical equation is introduced considering seepage law and production features of tight gas in Ordos basin [14][15]. With introducing superposition time function under variable production rate to derive simplified relationship between the dynamic reserves and the pseudo pressure regularization production [16][17], the new method only rely on regular production monitoring data with merits of little dependency of field pressure and stable working schedule.

Using actual field units, dynamic reserves calculated equation in tight gas reservoir is given as (7).

$$G = 5.6 \times 10^3 \frac{p_i S_{gi}}{Z_i \left( \mu_g c_i \right)} \left( \frac{1}{m_{pex}} \right)$$

(7)
And

\[
m(p) = \int_{p_0}^{p} \frac{p}{\mu(p)z(p)} dp
\]

\[
\tilde{m}_{ps} = \frac{-1}{q_g} \frac{dm(p)}{dt}
\]

(8)

Since \( \tilde{m}_{ps} \) is curve slope of normalized rate (\( p_{scr} \) is calculated from \( p_s \)) versus producing time, and \( m(p) \) is pseudo pressure. When the static parameters are constant, the calculated results of dynamic reserves depend on \( \tilde{m}_{ps} \). Actually, \( q_g \) will be changing all the time while directly using variable production rate under real producing time, which is leading to curve of normalized rate versus superposition time continuous fluctuation. With greater fluctuating of the curve, the slope of curve will be difficult to identify. As a result, utilizing superposition function to treat shifty rate and smooth curve is crucial to obtain the single slope then to realize precise numeration (figure 5).

Superposition time function can be shown in (9) from superposition theory.

\[
t_s = \sum_{i=1}^{n} (q_i - q_{i+1}) (t_n - t_{i+1})
\]

(9)

As shown in (10), \( \tilde{m}_{ps} \) changes to curve slope of normalized rate versus superposition time.

\[
\tilde{m}_{ps} = \frac{-1}{q_g} \frac{dm(p)}{dt_s}
\]

(10)

Figure 5. Curve of normalized rate vs. superposition time of well X-b.

Figure 6. P Dynamic reserves vs. production time for different type of classic wells in M gas field.

Combining (9) and (10) substitute into (7), the dynamic reserves of downhole throttling in tight gas reservoir can be obtained. The point is, the main data of the method to calculate the dynamic reserves is the production history of the gas well. Therefore, under basis of the longer producing time of the gas well, the shorter time of stopping production, curve of the superposition time function will be more regular and calculated reserves will be more accurate. For problems of short producing time (discharge radius of the dynamic reserves of a tight gas well varies with time), dynamic reserves for different production period (long period like 3–5 years, while short period as 1 year) can be calculated respectively for choosing typical wells in typical blocks by using this method. Then a revision chart can be obtained by using the ratio of the two (figure 6). For the gas well with a short history of production, the dynamic reserves of the gas well can be quickly corrected by using the revision chart.

4. Example and Application

4.1. Examples and reliability Demonstration
Taking X1 gas block in M gas field as an example (three kind of complicated wells are all included in M gas field), the first batch of gas wells were produced at 2010 with abundant pressure test data. The fluid boundary had near or already accessed to. The contrast result of these wells with using material balance equation/Fetkovich and new methods is shown in the figure 7. The result indicates that the average errors is about 6.7%. Furthermore, conventional methods usually take 1~3 years to wait for multiple pressure data while the new one requires 3~4 hours. It shows that the new methods are accurate and fast.

Therefore, with comprehensive application of above methods according to single well data and production characteristics in different gas areas, dynamic reserves can be tracked and estimated. The dynamic reserves evaluation technology of gas wells in low permeability and tight gas reservoirs is further supplemented and perfected by presented type of inadequate pressure test data in low permeability gas reservoir, water production, downhole throttling in tight gas reservoir. In the last 3 years, the ratio of dynamic reserves evaluation of M gas field in Ordos Basin is increased by 67%, which provides an important basis for the deployment of gas field and gas wells refracturing. This will also further enhance the utilization degree of gas reserves.

Figure 7. Contrast results of dynamic reserves in X1 gas block.

4.2. Reference for infilling wells
X2 gas block of M gas field equipped with south-north irregular well network in order to adapt heterogeneous characteristics. At prime stage, the range of well interval was about 1.5~2.5km, with average distance 2 km. The result of dynamic reserves appraising was $1.83 \times 10^8$m³ by average with limited control radium 0.76 km. Besides, considering uncompleted well network, infilling wells need to be deployed (figure 8). Finally, field pressure in the gas block of infilling wells was very close to original field pressure. Up to the present, through cumulative infilling 52 gas wells, M gas field constructs average gas productivity $4.1 \times 10^8$m³ per year.

Figure 8. Drainage radius of X2 gas block

4.3. Reference for gas well refracturing
Relying on results of dynamic reserve and dynamic-static characteristics, the wells which are contradictory with dynamic-static are selected to reform for improving degree of reservoir
development. There are two kinds of wells to choose as options to reform. On the one hand, wells of high dynamic reserve and low production rate were selected. For example, dynamic reserve of well X1 in M gas field was $1.8 \times 10^8 \text{m}^3$ with production rate $1.1 \times 10^4 \text{m}^3/\text{d}$. Acid-refracturing was conducted in Nov. 2014 to boost production rate to $2.3 \times 10^4 \text{m}^3/\text{d}$. On the other hand, wells of good physical reservoir and low dynamic reserve were selected. Taking well X2 in M gas field as an example, with effective height 7m, permeability 0.33mD and porosity 5.8% in well logging interpretation. Production rate for intermittent in prior stage was $1.0 \times 10^4 \text{m}^3/\text{d}$ only with dynamic reserve $1.13 \times 10^8 \text{m}^3$. Acid-refracturing was conducted in Oct. 2015 to boost production rate to $2.0 \times 10^4 \text{m}^3/\text{d}$. In the meanwhile, appraising dynamic reserves up to $2.34 \times 10^8 \text{m}^3$.

5. Conclusions
(1) Due to different flowing mechanism, water production characteristics and production model, dynamic reserves estimation methods of inadequate pressure test data in low permeability gas reservoir, water production, downhole throttling in tight gas reservoir are proposed. The approaches of new methods are accurate and fast which are easily implemented in desktop application or spreadsheet with minimal computational effort. Besides, the evaluation technology of the dynamic reserves of the gas wells in the low permeability and tight gas reservoir have further supplemented by new methods.

(2) As a result of applying this dynamic reserve appraising system, the ratio of evaluation wells in the M gas field of the Ordos Basin has increased by 67% in the past three years, and the material base for gas field development has been implemented. The new methods provide a direct reference for the deployment of gas infilling wells, gas wells refracturing, and further improve the utilization level of reserves. Finally, comprehensive tracing dynamic reserves in gas field are achieved.

Nomenclature

$p/p_o/p_i$—field pressure/wellhead pressure /original field pressure, MPa; $D$—wellbore pressure gradient, MPa/100m; $H$—depth of gas, m; $\Delta P_p$—Visual pressure difference, MPa; $G_p$—cumulative gas production, $10^8 \text{m}^3$; $\omega$—volume factor of water influx; $W_e$—water reflux, $10^4 \text{m}^3$; $W_p$—cumulative water production, $10^4 \text{m}^3$; $G$—dynamic reserve, $10^8 \text{m}^3$; $B_o/B_g$—volume factor under field pressure and original field pressure ; $Z/Z_i$—Z-factor of field pressure and Z-factor of original field pressure; $T/T_o/T_{sc}$—temperature of gas reservoir /original gas reservoir/ standard situation,K; $m(p)$—pseudo-pressure, MPa; $p_{uc}$—pressure under standard situation, MPa; $S_{og}$—original gas saturation,%; $\mu_g$—gas viscosity, $\text{mpa} \cdot \text{s}$ ; $C_i$—comprehensive compression coefficient; $q_i/q_{g}$—gas production rate at day i/ gas production rate, $10^4 \text{m}^3/\text{d}$; $t/t_s$—production time/superposition time, day.

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