# A material balance based method of determining the proportion of shale adsorbed gas production

Jinyou Dai [1,*], Yang Zhang [1], Daixin Chen [1], Shijia Zhao [1] and Xiaoyu Xu [1]

[1] College of Petroleum Engineering, China University of Petroleum (Beijing), China

**Abstract.**The production of shale adsorbed gas cannot be measured separately in the production process, and the method for determining the proportion of shale adsorbed gas output is insufficient. Desorption residual amount of adsorbed gas and free gas residual amount are introduced. Langmuir isothermal adsorption equation, shale gas well geology and production data are used. The analytical models of desorption residual amount of adsorbed gas, free gas residual amount of adsorbed gas and output ratio of adsorbed gas are derived respectively, and the method of determining output ratio of adsorbed gas based on material balance is established. The results show that the proportion of adsorbed gas output is low in the initial stage of shale gas production. With the extension of production time, the proportion of adsorbed gas output gradually increases, and the adsorbed gas plays an increasingly strong role in supporting the productivity of gas wells. To keep shale gas well exploitation for a long time is conducive to the full release of shale gas adsorption potential. This research is of practical significance and provides a new technical way for the study of shale adsorbed gas production.

**Keywords:** component; shale adsorbed gas; output ratio; determination method; material balance.

## 1. Introduction

Shale gas is a kind of unconventional natural gas resource with great potential. It is also an important field for increasing natural gas storage and production in China in the future [1-3]. Shale gas is mainly composed of adsorbed gas and free gas [4-6]. Among them, the adsorbed gas accounts for 25%-85%, with an average of about 50% [7-8]. Although the proportion of adsorbed gas in shale is high, but its production law is complicated. On the one hand, the unique adsorption characteristics of adsorbed gas lead to the constant change of the output proportion of adsorbed gas in the production process, and the output proportion is not equal to the occurrence proportion. At the same time, in the production process, the adsorbed gas is desorbed first and then produced, and its output is difficult to be measured separately, which further increases the difficulty of understanding the production law of adsorbed gas [9-11]. In particular, the method of determining the proportion of adsorbed gas production is relatively lacking, which limits the understanding of the law of adsorbed gas production, and interferes with the efficient exploitation and productivity prediction of shale gas to some extent. In view of the problems such as "it is difficult to measure the output of shale adsorbed gas and the lack of methods to determine the output proportion of shale adsorbed gas", it is crucial to establish a method to determine the output proportion of shale adsorbed gas in order to deepen the understanding of the production law of shale adsorbed gas. Therefore, this paper introduces desorption residual amount of adsorbed gas and free gas residual amount, and establishes a method to determine the proportion of shale adsorbed gas production based on material balance, which provides a new technical way for the study of shale adsorbed gas production law.

## 2. Method principle

Two indexes, such as adsorption gas desorption residual and free gas residual are introduced. Analytical models for the evaluation of adsorption gas desorption residual, free gas residual and adsorption gas output ratio are derived by using Langmuir isothermal adsorption equation, shale gas well geology and production data.

**2.1 Residual amount of adsorption gas desorption**

In shale gas reservoirs, adsorbed gas and free gas are in dynamic equilibrium. When the temperature and pressure conditions of the gas reservoir change, this equilibrium relationship will be destroyed, and the adsorbed gas and free gas will transform into each other [12-13]. Generally, the proportion of adsorbed gas decreases with the increase of temperature, while the proportion of adsorbed gas increases with the increase of pressure [14-16]. The production process of shale gas is a typical isothermal depressurization process. The unidirectional conversion of adsorbed gas to free gas and the mixed output of desorption adsorbed gas and free gas are the remarkable characteristics of this process. The change of adsorbed gas volume can be described by isothermal adsorption equation.

Previous studies have shown that the adsorption gas is mainly methane, and its adsorption on the pore surface belongs to supercritical physical adsorption [17-19], and its isothermal adsorption curve is a type I isotherm, which can be expressed by Langmuir isothermal adsorption equation [20-21] :

$$V_a = V_L \frac{p}{p + p_L} \tag{1}$$

$V_a$ -Adsorbed gas, $m^3/t$;

$V_L$ - Lannister volume, $m^3/t$;

$p_L$ - Lannister pressurem $MPa$;

$p$ - Formation pressurem $MPa$ 。

Given the original adsorption gas volume ( $V_{a0}$ ) in the initial stage of production and the adsorption gas volume ( $V_{ai}$ ) in the production process, the adsorption gas desorption amount ( $V_{di}$ ) in the production process can be expressed as:

$$V_{di} = V_{a0} - V_{ai} \tag{2}$$

$V_{di}$ - Adsorption gas desorption amount， $m^3/t$;

$V_{a0}$ - Original adsorption gas volume， $m^3/t$;

$V_{ai}$ - The adsorption gas volume， $m^3/t$ 。

The Langmuir isothermal adsorption equation under the original pressure and production pressure is substituted into equation (2), and the following results can be obtained:

$$V_{di} = V_L p_L \frac{(p_0 - p_i)}{(p_0 + p_L)(p_i + p_L)} \tag{3}$$

$p_0$ - Original formation pressure， $MPa$;

$p_i$ - Producing formation pressure， $MPa$ 。

The residual desorption amount of adsorbed gas (the difference between adsorbed gas desorption amount and adsorbed gas cumulative yield) is introduced, and the output curve function of shale gas well is set to be $q = f(t)$ and the proportion function of adsorbed gas output is $x = g(t)$, then the residual desorption amount of adsorbed gas in the production process ( $V_{ri}$ ) can be expressed as:

$$V_{ri} = V_{di} - N'_{pi} = V_{di} - \frac{\int_1^i x(t)q(t)dt}{Ah\rho_b} = V_{di} - \frac{\sum_{k=1}^{i} x_k q_k}{Ah\rho_b} \quad i = 1, 2, \cdots\cdots n \tag{4}$$

$V_{ri}$ -Adsorption gas desorption residual amount， $m^3/t$;

$N'_{pi}$ -Adsorption gas production， $m^3/t$;

$q_k$ -Daily gas production， $m^3$;

$x_k$ - Adsorption gas output ratio，%；

$A$ - Well controlled gas bearing area， $m^2$ ；

$h$ - Effective well control thickness， $m$ ；

$\rho_b$ -Shale density， $t/m^3$ ；

$i$ -Production days；

$n$ -Cumulative days of production。

## 2.2 Free gas residue

The free gas is the sum of desorption adsorption gas and the original free gas. The free gas volume is the sum of desorption amount of adsorbed gas and the original free gas volume.

With the prolongation of gas well production time, desorption amount of adsorbed gas gradually increases, and the original free gas volume remains unchanged, so the free gas volume continues to increase. Some of the free gas is extracted and some of it remains underground. To this end, free gas residue (the difference between free gas and cumulative gas production) is introduced:

$$V_{ti} = V_{f0} + V_{di} - N_{pi} = V_{f0} + V_{di} - \frac{\int_1^i q(t)dt}{Ah\rho_b} = V_{di} - \frac{\sum_{k=1}^{i} q_k}{Ah\rho_b} \qquad i = 1, 2, \cdots\cdots n \tag{5}$$

$V_{ti}$ -free gas residue， $m^3/t$ ；

$V_{f0}$ -initial free gas volume， $m^3/t$ ；

$V_{di}$ -adsorption gas desorption capacity， $m^3/t$ ；

$N_{pi}$ -cumulative gas production， $m^3/t$ ；

In formula (5), the original free gas content ($V_{f0}$) is:

$$V_{f0} = \frac{\phi S_{g0}}{\rho_b} \cdot \frac{p_0 T_{sc}}{z_0 p_{sc} T_0} \tag{6}$$

$V_{f0}$ -initial free gas volume； $m^3/t$ ；

$\varphi$ -effective porosity；

$S_{g0}$ -initial gas saturation；

$T_{sc}$ -ground surface temperature, $K$ ；

$z_0$ -original gas compression factor；

$p_{sc}$ -ground surface pressure， $MPa$ ；

$T_0$ -gas reservoir temperature， $K$ 。

## 2.3 Adsorption gas output ratio

Based on the principle of material balance, for any production time node of shale gas well, the ratio of shale adsorbed gas output ( $x_i$ ) should be the ratio of adsorbed gas desorption residue and free gas residue at the time node:

$$x_i = \frac{V_{ri}}{V_{ti}} \times 100\% = \frac{V_{di} - \sum_{k=1}^{i} x_k q_k / Ah\rho_b}{V_{f0} + V_{di} - \sum_{k=1}^{i} q_k / Ah\rho_b} \times 100\% \qquad i = 1, 2, \cdots\cdots n \tag{7}$$

$x_i$ - Adsorption gas output ratio，%；

$V_{ri}$ - Adsorption gas desorption residual amount， $m^3/t$；

$V_{ti}$ - Free gas residue， $m^3/t$；

The formula (7) can be solved by iterative method. The iterative formula is as follows:

When $i=1$：

$$x_1=\frac{V_{r1}}{V_{t1}}=\frac{V_{d1}}{V_{f0}+V_{d1}}\times 100\% \quad (8)$$

When $i>1$：

$$x_i=\frac{V_{ri}}{V_{ti}}=\frac{V_{di}-(\sum_{k=1}^{i-1}x_k q_k)/Ah\rho_b}{V_{f0}+V_{di}-\sum_{k=1}^{i-1}q_k/Ah\rho_b}\times 100\% \quad (9)$$

The above three evaluation models together constitute a method for determining the proportion of shale adsorbed gas production based on material balance.

In the following, a production example of a shale gas well is calculated using this method.

## 3. Calculation examples

Well Y is a shale gas well in Changning - Weiyuan gas field. The production layer is Longyi Member 1 Submember of Longmaxi Formation of Lower Silurian System, with a buried depth of 3830m. The well controlled gas bearing area of this well is 0.5km2, effective thickness is 38m, shale density is 2.54g /cm3, effective porosity is 5.1%, original gas saturation is 63%, original gas compression factor is 1.24, Lannister volume is 1.5m3 /t, Lannister pressure is 8 MPa. The original formation pressure is 56.5MPa, the original formation temperature is 122℃, the ground pressure is 0.1013MPa, and the ground temperature is 25℃ (Table 1).

Table 1 Basic parameter table of well A shale interval

| Control the gas bearing area of a single well $A$ (km2) | net pay thickness $h$ (m) | density of rock $\rho_b$ (g/cm3) | effective porosity $\varphi$ (%) | initial gas saturation $s_{g0}$ (%) | original gas compression factor $z_0$ |
|---|---|---|---|---|---|
| 0.5 | 38.0 | 2.54 | 5.1 | 63 | 1.24 |
| Lannister volume $V_L$ (m3/t) | Lannister pressure $p_L$ (MPa) | initial formation pressure $p_0$ (MPa) | original formation temperature $T_0$ (℃) | ground surface pressure $p_{sc}$ (MPa) | ground surface temperature $T_{sc}$ (℃) |
| 1.5 | 8 | 56.5 | 122 | 0.1013 | 25 |

According to the calculation of parameters in Table 1, it can be seen that the original adsorbed gas ($V_{a0}$) of shale is 1.31m3/t, the original free gas ($V_{f0}$) is 4.29 m3/t, and the total gas content is 5.6 m3/t. The proportion of adsorbed gas in shale is 23.4%. The production curve of well Y (FIG.1) shows that the well started production on September 9, 2019 and by June 17, 2020 the cumulative gas production was 21.9×106m3. In the production process, the daily gas production decreased rapidly at the initial stage, and stabilized after 1 month. The overall daily gas production ranged from 4×104m3/d to 20×104m3/d, with an average of 5.4×104m3/d. The casing pressure and formation pressure of gas well generally show a downward trend. Under the influence of controlled pressure limiting production and shut-in, the casing pressure fluctuates and jumps locally.

According to the above geological and production data, formulas (1) - (9) are used to calculate the proportion of adsorbed gas output at each production time node of the gas well. The results show that (Fig. 2) : With the prolongation of production time, the proportion curve of adsorbed gas output in well Y shows a regular upward trend. Under the influence of factors such as controlled pressure limiting production and well shut-in, there are certain local fluctuations in the curve. In the initial stage of production (4.9. 2019), the proportion of adsorbed gas output was lower (0.01%). By 6.17. 2020, the output ratio reached 2.76%.It shows that the contribution of adsorbed gas output to gas well production will increase with the prolongation of production time. According to the calculation results of adsorbed gas output ratio, the correlation curve between adsorbed gas output ratio and production time was drawn (Fi. 3). It can be seen that the output proportion of adsorbed gas is positively correlated with the production time. The relevant formula is $y = 0.1753x + 0.2097$($R^2 = 0.9979$). The increase rate of adsorbed gas output ratio is 0.1753%/ mon.

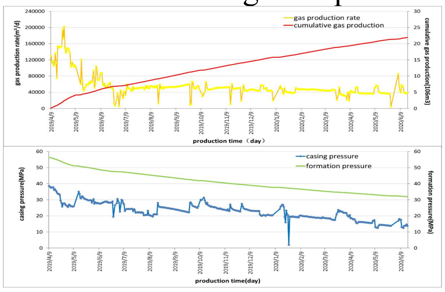


Figure. 1 Production curve of Well A

From the production experience of shale gas fields abroad, the production life of shale gas wells can reach 30 years or even longer. According to the correlation between the adsorbed gas output ratio and production time of well Y, the adsorbed gas output ratio will reach 50% if well Y produces for 285 months (or 23.8 years) continuously. At 360 months (or 30 years) of continuous production in well Y, the proportion of adsorbed gas produced will reach 63.3%. This shows that free gas is the main body of productivity in the early stage of shale gas well production. With the prolongation of production time, adsorbed gas plays an increasingly prominent role in supporting production capacity. In the later stage of production (for example, 23.8 years of production in well Y), adsorbed gas will become the main body of gas well productivity. Therefore, the long-term production of shale gas wells is very important for the full release of adsorbed gas potential.

## 4. Conclusion and Understanding

1） Shale gas production is an isothermal depressurization process. The unidirectional conversion of adsorbed gas to free gas and the mixed output of desorption adsorbed gas and free gas is a significant feature in shale gas production.

2）The method introduces two indexes, such as the desorption residual amount of adsorbed gas and the free gas residual amount, and establishes a method to determine the output proportion of shale adsorbed gas based on material balance. This method can quantitatively calculate the proportion of adsorbed gas production at any production time node of shale gas well, and provides a new technical way for the study of adsorbed gas production law of shale gas.

3）The calculation example shows that the proportion of adsorbed gas output is low in the initial stage of shale gas production. With the extension of production time, the proportion of adsorbed gas output gradually increases, and the adsorbed gas plays an increasingly strong role in supporting the productivity of gas Wells. Keeping shale gas well long term exploitation is conducive to the full release of adsorbed gas potential.

## References

[1] Yan CZ,Huang YZ,Ge CM,et al. Shale gas: enormous potential of unconventional natural gas resources[J]. Natural Gas Industry. 2009,29(5): 1-6.

[2] Shi XB,Yang HH,Fan XY,et al. New methods for shale gas reserves calculation[J]. Natural Gas Industry. 2012,32(4): 60-62,123-124.

[3] Wang WF,Liu P,Chen C,et al. The study of shale gas reservoir theory and resources evaluation[J]. Natural Gas Geoscience. 2013,24(3): 429-438..

[4] Zhang JC,Jin ZJ,Yuan MS. Reservoiring mechanism of shale gas and its distribution[J]. Natural Gas Industry. 2004,24(7): 15-18.

[5] Wu Keliu, Li Xiangfang,Chen Zhangxing. Micro-scale effects of gas transport in organic nanopores of shale gas reservoirs[J]. Natural Gas Industry, 2016, 36(11): 51-64.

[6] Zhang Yanyu, Li Dongdong,Sun Xiaofei,et al. A new model for calculating the apparent permeability of shale gas in the real state s[J]. Natural Gas Industry,2017,37(11):53-60.

[7] John B. Curtis. Fractured Shale-Gas Systems[J]. AAPG Bulletin, 2002, 86(11) : 1921-1938.

[8] SHI Wen-rui,GUO Mei-yu,ZHANG Zhan-song,et al.Case Study on Adsorption and Desorption Gas Experiment Measurement of Shale Gas [J]. Science Technology and Engineering,2015,15(07):167-172.

[9] Zhang JC,Xue H,Bian CR,et al. Remarks on unconventional gas exploration in china[J]. Natural Gas Industry. 2006,26(12): 53-56.

[10] Geng LX,Cao YS. Interpretation of the calculation and evaluation of shale gas resources / reserves[J]. Unconventional Oil & Gas. 2015,2(1): 10-14.

[11] Li Y X， Qiao D W， Jiang W L， et al. Gas content of gas-bearing shaleand its geological evaluation summary. Geological Bulletin of China，2011,30(Z1):308-317.

[12] Ross DJK,Bustin RM. Shale gas potential of the Lower Jurassic Gordondale member,Northeastern British Columbia,Canada[J]. Bulletin of Canadian Petroleum Geology. 2007,55(1): 51-75.

[13] Ross DJK,Bustin RM. Characterizing the shale gas resource potential of Devonian Mississippian strata in the Western Canada sedimentary basin: Application of an integrated formation evaluation[J]. AAPG Bulletin,2008,92(1): 87-125.

[14] Chalmers RL,Bustin RM. Lower Cretaceous gas shales in Northeastern British Columbia,Part II: Evaluation of regional potential gas resources[J]. Bulletin of Canadian Petroleum Geology. 2008,56(1): 22-61.

[15] Raut U,Fam M,Teolis BD,et al. Characterization of porosity in vapor-deposited amorphous solid water from methane adsorption[J]. The Journal of Chemical Physics. 2007,127: 1-6.

[16] Li JJ,Yan XT,Wang WM,et al. Key factors controlling the gas adsorption capacity of shale: A study based on parallel experiments[J]. Applied Geochemistry. 2015,58: 88-96.

[17] Zhou CN, Zhu RK, Bai B, et al. First discovery of nano-pore throat in oil and gas reservoir in China and its scientific value[J]. Acta Petrologica Sinica. 2011, 27(6): 1857-1864.

[18] Yang F, Ning ZF, Zhang R, et al. Investigations on the methane sorption capacity of marine shales from Sichuan Basin, China[J]. International Journal of Coal Geology. 2015, 146: 104-117.

[19] Sheng M, Li GS, Chen LQ, et al. Mechanisms analysis of shale-gas supercritical adsorption and modeling of isorption adsorption[J]. Journal of China Coal Society. 2014, 39(S1): 179-183.

[20] Zhou L, Lv CZ, Wang YL, et al. Physisorption of Gases on Porous Solids at Above-Critical Temperatures[J]. Progress in Chemistry. 1999, 11(3): 221-226.

[21] Liu Y, Tang SF, Yao YF, et al. Supercritical adsorption and desorption characteristics and influencing factors for the shale gas[J]. Petroleum Geology and Oilfield Development in Daqing. 2015,34(2): 170-174.

[22] ZHANG Dongxiao,YANG Tingyun.An overview of shale-gas production[J].Acta Petrolei Sinica,2013,34( 4) : 792 -801.