

# Productivity Testing and Analysis of Low Permeability and Thick Layer of N Gas Field

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**Abstract:** For a better guidance of production, a combination of drill stem testing (DST), regional statistical method and pseudo steady-state seepage theory model was used to analyze the productivity of N gas reservoir in light of the complex geological features of the low-permeability thick-layer. Firstly, the DST method was used to test the N gas reservoir. And then the binomial pseudo-pressure method, binomial pressure square method and exponential method were used to interpret the test data of DST of this formation. Finally, the binomial pseudo-pressure interpretation method was used and the results showed that only the productivity of H3b layer was successfully tested of the four. The H3a, H4b and H5a layers are ultra-low pore and permeability gas reservoirs and the productivity of these layers can't be explained by the available data due to the short testing time and a non-stationary state of testing pressure and quantity, resulting in the failure of the test. The productivity of the main layers were estimated and forecasted by the regional statistical method and the theoretical model of pseudo steady-state seepage, taking the arithmetic average value of the regional statistical method and the theoretical formula as the final value of absolute open flow rates(AOF). The final calculation results are as follows: the AOF of main gas layers H3a, H3b, H4b and H5a in N gas field is  $31.30 \times 10^4 \text{m}^3/\text{d}$ ,  $388.92 \times 10^4 \text{m}^3/\text{d}$ ,  $20.82 \times 10^4 \text{m}^3/\text{d}$  and  $30.80 \times 10^4 \text{m}^3/\text{d}$ , respectively. This method may shed light on verifying and calculating the productivity of gas wells and determining the reasonable production allocation of gas wells.

## 1. Introduction

The low-permeability gas reservoirs in China are rich in resources and have great development potential. At present, many scholars at home and abroad have conducted corresponding research on the production capacity prediction of low permeability gas reservoirs.

DST is a work aiming at obtaining the parameters of the oil and gas layer under dynamic conditions, evaluating the oil and gas layer timely and accurately after encountering the oil and gas display in the process of drilling to obtain a temporary completion test for reservoirs. DST is commonly used in Productivity prediction because of the characteristics of reducing drilling cost, improving oil testing speed and discovering oil and gas layers in time. Due to its limited self-spraying capacity, DST is generally applied to medium-high permeability gas reservoirs rather than low permeability ones [2]. However, with the development of technology, DST has been successfully applied in conventional oil and gas reservoirs, high temperature and high pressure oil and gas reservoirs [3-5], coalbed methane reservoirs [6-7],

high sulfur gas reservoirs and low permeability tight sandstone oil and gas reservoirs [8-12], and achieved good results. N gas field is a low-permeability gas field with strong heterogeneity. During the production process, multiple DSTs were carried out.

The regional statistical is a method to regression the statistical samples and obtain the relationship between the unit thickness absolute open flow rate and the log permeability using more relevant gas reservoir productivity test data [13-14], which is often used in the absence of data or in the case of insufficient data. This paper combines the productivity test data of typical low-permeability gas fields to predict the productivity of N gas field.

The seepage theory model is derived by the formula method, which refers to using the principle of seepage mechanics, considering the seepage characteristics of gas reservoir, and using the relevant productivity formula to calculate. In terms of the production characteristics of N thick gas reservoirs, due to the degree of gas well opening, skin effect in the near wellbore zone and the non-Darcy effect on productivity, productivity cannot be evaluated

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by a single plane radial flow or ball-to-heart flow capacity equation. So we use a pseudo steady-state productivity equation combining plane radial flow and ball-oriented flow, and the result is more in line with the actual [15-18].

N gas reservoir is a heterogeneous gas reservoir with low permeability and thick layers, and the gas reservoir is not fully open, some gas Wells have carried out stimulation operations, and the productivity is difficult to predict. Therefore, single productivity prediction method is not good enough. Through the combination of various methods, optimization is carried out to finally determine the productivity of different production layers [19].

## 2.Productivity test

### 2.1.DST

In the N gas field, eight DSTs have been carried out for six layers including H1a, H2c, H3a, H3b, H4b and H5a, which were tested by four wells. Four DSTs have been carried out for N1 well, including lower H3B layer, upper H3B layer, H2C layer and H1a layer; One DST has been carried out for N2 well, with H5a layer; Two DSTs have been carried out for N3 well, with H4b layer and H3a layer; One DST has been carried out for N4 well, with H4b layer. According to the DST profile of each well, representative productivity test data were obtained in five of the nine tests. The following table explains and analyzes the productivity of the main layer for representative test data.

**Table 1** DST statistics for N gas field.

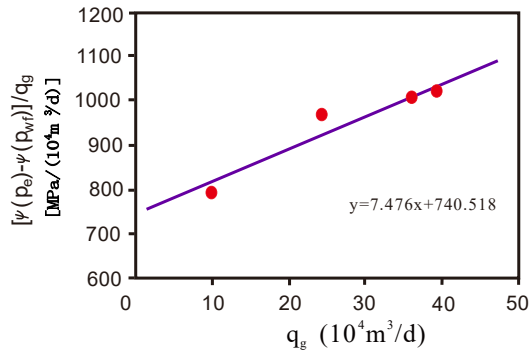
Well No	Test number	Test layer	Original formation pressure	Whether it is representative productivity data	Test failure reason	Whether it is main layer
N1	DST1	Under H3b	Measured	Yes	/	Yes
	DST2	upper H3b	Measured	Yes	/	Yes
	DST3	H2c	Maximum recovery pressure	No	Not tested	No
	DST4	H1a	Measured	No	Test time is short, pressure and flow are not stable	No
N2	DST2	H5a	Measured	No		Yes
N3	DST1	H4b	Maximum recovery pressure	No		Yes
	DST1A	H4b	Not tested	No		Yes
	DST2	H3a	Measured	No		Yes
N4	DST1	H4b	Measured	No	Yes	

From June 4th to June 11th, 2013, the DST was applied to N1 well on the upper H3b layer (the depth of the perforation section is 3709m-3739m), and the gas test results are shown in table 2. The binomial pseudo-pressure method, binomial pressure plane method and

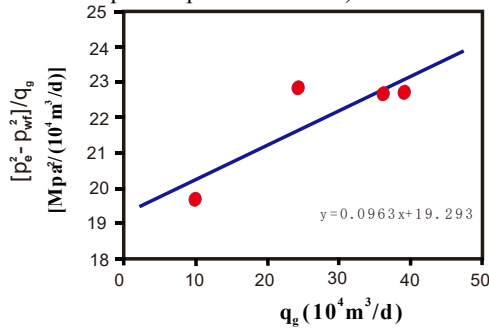
exponential method were respectively adopted to interpret the DST data of H3b layer. The results are shown in Fig.1~ Fig.3 are the gas test interpretation result curves of different methods, and the IPR curve is shown in Fig.4.

**Table 2** Test results of the upper H3b layer in N1 well

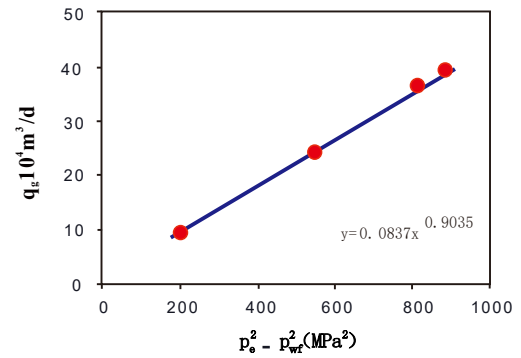
Level number	Perforated interval, m	Pi, MPa	Pwf, MPa	Daily productivity, 10 <sup>4</sup> m <sup>3</sup>
Upper H3b	3709-3739	36.84	34.05	10.041
			28.26	24.4974
			23.2	36.2298
			21.58	39.3198



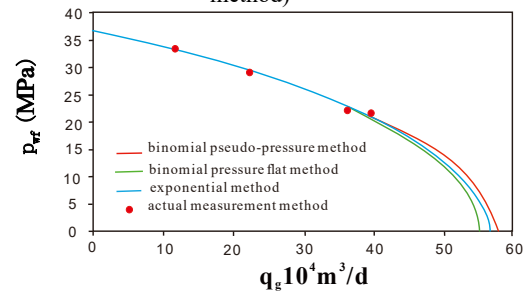
**Figure1** test interpretation for upper H3b layer (binomial pseudo-pressure method)



**Figure2** test interpretation for upper H3b layer (binomial pressure flat method)



**Figure3** test interpretation for upper H3b layer (exponential method)

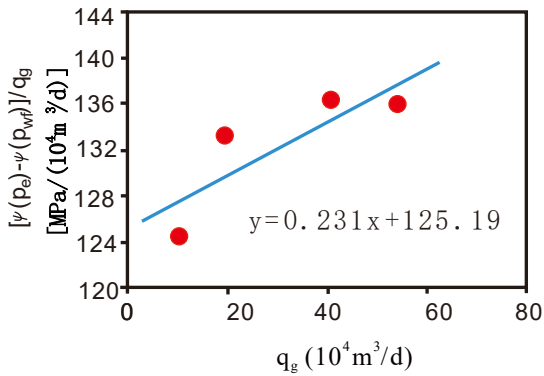


**Figure4** IPR curve in the upper H3b layer

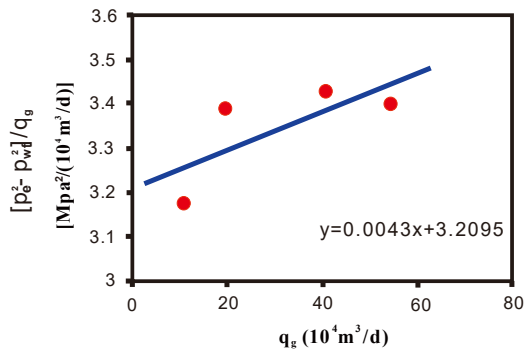
From May 21st to June 3rd, 2013, the DST was applied to N1 well on the lower H3b layer (the depth of the perforation section was 3769m-3799m), and the gas test results are shown in table3. The binomial pseudo-pressure method, binomial pressure plane method and exponential method were respectively adopted to interpret the DST data too. The results are shown in Figure5~figure7 are the gas test interpretation result curves of different methods, and the IPR curve is shown in Figure8.

**Table3** Test results of the lower H3b layer in N1 well

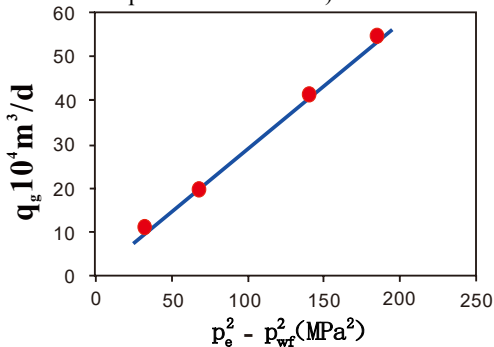
Level number	Perforated interval, m	Pi, MPa	Pwf, MPa	Daily production capacity, 10 <sup>4</sup> m <sup>3</sup>
Lower H3b	3769.0~3799.0	36.947	36.02	19.9814
			35.57	28.1341
			34.99	41.0598
			34.35	54.4824
			36.48	10.8058
			34.54	53.5364



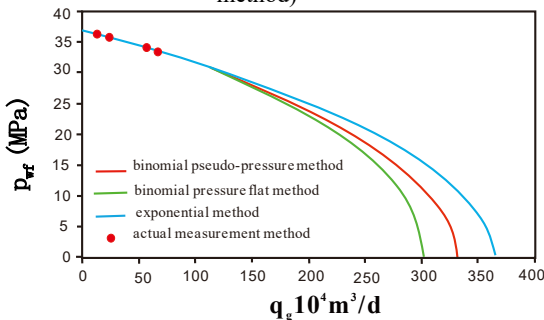
**Figure5** test interpretation for lower H3b layer (binomial pseudo-pressure method)



**Figure6** test interpretation for lower H3b layer (binomial pressure flat method)



**Figure7** test interpretation for lower H3b layer (exponential method)



**Figure8** IPR curve in the lower H3b layer

It can be seen from the table that there is a difference in the AOF obtained by different methods. In view of the

**Table 4** Results of regional statistical method for predicting the productivity of the main layer

Layer	Thickness ,m	Permeability ,mD	AOF,10 <sup>4</sup> m <sup>3</sup> /d
H3a	31.8	1.14	27.57
H4b	57.4	0.41	23.84
H5a	62.3	0.52	30.12

fact that the binomial pseudo-pressure interpretation method is based on the gas seepage theory, the interpretation results have a high degree of confidence. So the ultimate AOF on the upper H3b layer and lower H3b layer of the N1 well is calculated by the pseudo-pressure interpretation method. The AOF on the upper H3b layer and lower H3b layer is 57.38×104m3/d, 331.06×104m3/d.

## 2.2.Regional Statistics Method

Only the H3b layer has been successfully tested for productivity with DST in the upper section of the Huagang formation of N gas field. Due to the ultra-low characteristics of porosity and permeability of H3a, H4b and H5a layers and the short test time, the pressure and output have not reached a stable state, and the existing data cannot explain the productivity of these layers, resulting in the failure of the test.

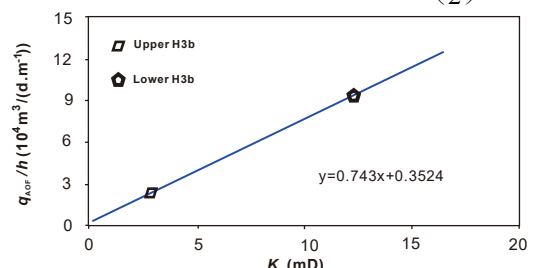
The regional statistical method and the pseudo steady-state seepage theory model were used to estimate and predict the productivity of the untested main layer (H3a layer and H4b layer of N3 well, H5a layer of N4 well).

Example of the method: Based on the method of DST, the statistical relationship between AOF and logging permeability for H3B of N gas field is as follows (as figure 9) :

$$q_{AOF} = 0.743 \times Kh + 0.3524 \times h \quad (1)$$

Due to the small number of samples, the statistical formula should not be directly used for productivity prediction. Therefore, combining the productivity test data of typical low permeability gas fields in China, including Yanchang field, Yulin gas field, Sulige gas field and Daniudi gas field, etc. The relationship between the AOF of per unit thickness and the log permeability with a large statistical sample size:

$$q_{AOF} = 0.6188 \times Kh + 0.1617 \times h \quad (2)$$

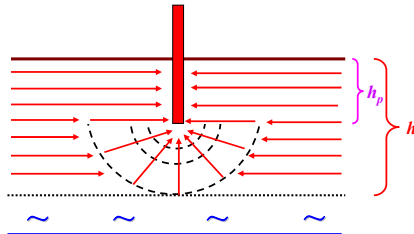


**Figure9** q<sub>AOF</sub> / h ~ K statistical relationship curve

Using the regression regional statistical formula (Equation3), the productivity of the untested main gas layer in the N gas field predicted is 23.84~30.12×104m3/d. The specific results are shown in the table4.

### 2.3.Capacity test of pseudo steady-state seepage theory model

For N-thick gas reservoirs with heterogeneous, the opening degree is not perfect. According to the principle of seepage mechanics and considering the seepage characteristics in the wells, the calculation formula of productivity is established. The model diagram is as Figure10.



**Figure10** Seepage diagram of Wells with imperfect opening degree of thick reservoir

For the opening layers, the productivity formula of the plane radial flow considering the skin effect and the non-Darcy flow characteristics is derived according to the gas pseudo-stabilized seepage theory. In the vertical region of  $h_p$ , the binomial equation of the plane radial flow is as follows:

$$p_e^2 - p_{wf}^2 = \frac{1.291 \times 10^{-3} T Z \mu}{K h_p} D_1 q_{sc1}^2 + \frac{1.291 \times 10^{-3} T \mu Z}{K h_p} \left( \ln \frac{0.472 r_e}{r_w} + S \right) q_{sc1} \quad (3)$$

$$D_1 = 2.191 \times 10^{-18} \frac{\beta \gamma_g K}{\mu h_p r_w} \quad (4)$$

For some layers that are not opened (Zone  $h - h_p$ ), in the vicinity of the wellbore, the form of the spherical

centripetal flow and the plane radial flow are combined. According to the pseudo steady-state seepage theory, the spherical centripetal flow productivity formula considering the formation pollution and the non-Darcy flow is derived. There is the binomial equation as follows:

$$p_e^2 - p_{wf}^2 = \frac{1.291 \times 10^{-3} Z \mu T}{K r_w} D_2 q_{sc2}^2 + 1.291 \times 10^{-3} Z \mu T \left[ \frac{1}{K r_w} \left( 1 - \frac{9}{5} \frac{r_w}{h - h_p} + S_1 \right) + \frac{1}{K (h - h_p)} \ln \frac{0.472 r_e}{h - h_p} \right] \quad (5)$$

$$D_2 = 7.032 \times 10^{-19} \frac{\beta \gamma_g K}{\mu} \left( \frac{1}{r_w^2} - \frac{r_w}{(h - h_p)^3} \right) \quad (6)$$

Where:  $h$ —thickness of gas layer, m;  $q_{sc1}$ —gas production in standard state,  $m^3/d$ ;  $K$ — effective permeability, mD ;  $\mu$ — gas viscosity, mPa·s;  $Z$ —Z-factor;  $T$ — gas layer temperature, K;  $h_p$ — opening thickness of gas layer, m;  $r_w$ —wellbore radius, m;  $D$ — turbulence coefficient;  $r_e$ —drainage radius, m;  $P_e$ — formation pressure, MPa;  $P_{wf}$ —bottomhole pressure (MPa);  $\beta$ —velocity coefficient,  $\beta = 7.644 \times 10^{10} / K_s^{1.5}$ ,  $m^{-1}$ ;  $S$ —skin coefficient;  $\gamma_g$ — relative density.

For the thick gas reservoir partially opened, the plane radial flow and the spherical centripetal flow simultaneously exist, so the total gas production  $q_{sc}$  in the gas well is the sum of the gas flows under the two seepage conditions:

$$q_{sc} = q_{sc1} + q_{sc2} \quad (7)$$

Based on the established pseudo steady-state seepage theory model ,the AOF of main layers H3a, H4b and H5a in N gas field is 21.28 ~ 27.912×104m3/d, as shown in the following table.

**Table5** the productivity predicting results of N gas field

Parameter layer	H (m)	K (mD)	pe (MPa)	T (K)	$\gamma_g$	$\mu$ (mPa.s)	$r_w$ (m)	$r_e$ (m)	$q_{AOF}$ ( $10^4 m^3/d^3$ )
H3a	31.8	1.14	36.64	421.3	0.615	0.025	0.1015	500	35.03
H4b	57.4	0.41	45.57	437.5	0.615	0.028	0.1015	500	17.8
H5a	62.3	0.52	53.99	446	0.615	0.030	0.1015	500	31.49

### 3. Result analysis

Regarding the final value of the productivity of each main gas layer in the gas field, the following principles are applied:

First, for the gas layer with DST data, as far as

**Table6** Summary of AOF of various gas layers in N gas field

AOF Layer	Unit: $10^4 m^3/d^3$			
	DST	Regional statistical formula	Pseudo steady-state seepage theory model	The values
H3a		27.57	35.03	31.30
Upper H3b	57.38			57.38
Lower H3b	331.54			331.54
H4b		23.84	17.80	20.82

possible, the results of the DST shall prevail;

Second, for the gas layer without DST, the arithmetic mean of the results calculated by the regional statistical method and the theoretical formula is taken as the final value of the AOF.

Based on the two principles above, the AOF of each gas layer in N gas field is determined as follows (table 6):

H5a		30.12	31.49	30.80
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It can be seen from Table8 that the AOF of the main gas layers H3a, H3b (including upper H3b and lower H3b), H4b and H5a of the N gas field are  $31.30 \times 10^4 \text{m}^3/\text{d}$ ,  $388.92 \times 10^4 \text{m}^3/\text{d}$ ,  $20.82 \times 10^4 \text{m}^3/\text{d}$  and  $30.80 \times 10^4 \text{m}^3/\text{d}$ .

#### 4.Conclusion

(1) Using DST, regional statistical method and pseudo steady-state seepage theory model to evaluate the productivity of N low- permeability gas reservoir. The method is simple and practical, less time consuming and low cost. With the comparing of a variety of methods, the results are reliable and easy to promote.

(2) For thick heterogeneous gas reservoirs, it is not possible to simply use single plane radial flow or spherical centripetal flow to evaluate the productivity. For the opening part of the layer, it is regarded as plane radial flow. For some layers that are not open, it is regarded as spherical centripetal flow. The pseudo steady-state seepage theory model is adopted to superimpose the productivity of the two, and the calculation results are more consistent with the actual production situation.

(3) When using the DST to evaluate the productivity of the gas well, the AOF explained by the binomial pseudo-pressure method is more reliable ; For the gas well that cannot be explained by the DST, when the regional statistical method is used for evaluation, In addition to the hole-permeability-saturated relationship fitted by the DST method, it is also necessary to find more productivity test data of gas wells with similar properties, and to regress the relationship between the AOF and the permeability to ensure its practicability; The pseudo steady-state seepage theory model should satisfy the actual geological conditions and seepage conditions as much as possible, and select the appropriate seepage equation to solve.

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