The Productivity Equation for Giant Thick Gas Reservoirs with Bottom Water

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Key words: Water drive gas reservoirs, non-Darcy flow, Radial flow, Hemispheric flow, Opening degree, Productivity equation

Abstract: For the production formulas of the gas reservoirs with bottom water, the models established in the past consider that only a small part of the gas layer is perforated and the entire region under the perforated zone is considered as the hemispheric flow, ignoring effects of the opening degree and formation anisotropy for gas production. The reality illustrates that the thick gas reservoirs may be larger opening degree and the flow hemispherical only exists near wellbore. The opening degree and the stratum anisotropy have great influence on production of gas well. Based on the previous models, this paper improves the models and deduces the productivity equation considering skin effect and the gas non-Darcy flow characteristics of the thick gas reservoirs with bottom water and analyzes the influence of the opening degree on the gas well productivity. The results of the examples show that the equations considering the skin effect, the non-Darcy flow and formation anisotropy are more realistic.

Introduction

Bottom water coning is an important factor to influence gas reservoir production rate [1-4]. As for the development of thick bottom-water reservoirs, to slow or even prevent the effect of bottom water coning, the producing wells usually partially penetrate the gas layer. Previous models [5-6] only took into account gas well opening degree is small (less than 1/3 the thickness of the gas layer), and considered the bottom hole as a hemispherical flow across the region. However, for actual thick bottom-water reservoir, gas well may be big opening degree (above 1/2the thickness of the gas layer), so the entire area in the bottom can't be simply considered as a hemispherical flow. In perforated zone it is a planar radial flow and below perforated zone it is a combination of a hemispherical flow and a planar radial flow. And because of the effects of formation anisotropy, the permeability of hemispherical flow area can’t be simply replaced with horizontal or vertical permeability. Meanwhile, in the process of real gas well productivity calculation, such as high gas rate well, fluid seepage velocity near wellbore area is too large to cause a high-speed non-Darcy flow, if not considering the non-Darcy effect, also lead to results mistake [7]. Based on percolation mechanism of the thick block bottom water gas reservoir, the author improved the formula derived by Zhang Qinghui [6] and deduced new gas well productivity equation considering the high-speed non-Darcy effect, skin pollution and formation anisotropy.

Model Establishment and Formula Derivation

Supposing there is a huge thick bottom water block gas reservoir, whose gas layer thickness is h. Within the scope of the perforated interval h_P, gas flow is planar radial flow; within the scope of the h-h_P under the bottom hole, the gas flow near wellbore area is hemispherical flow, and the gas flow far wellbore area is still planar radial flow. For such a kind of considering the actual situation of gas reservoir, the model is shown in fig. 1:

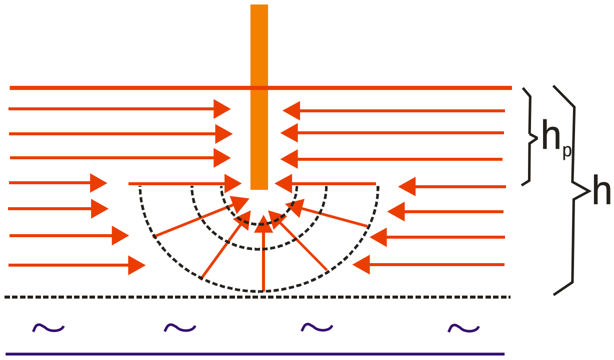

Fig. 1 Open degree imperfect well seepage flow diagram

Productivity Equation of Open Gas Layer Segments

Supposing the production of the gas reservoir upper portion is q_{sc1}, the production formula [8] considering the bottom skin effect and the gas non-Darcy flow characteristics can be calculated by:

$$p_e^2 - p_{wf}^2 = \frac{1.291\times10^{-3} q_{sc1} T \overline{m} \overline{Z}}{K_h h_p}\left(\ln\frac{r_e}{r_w} + S + D_1 q_{sc1}\right) \qquad (1)$$

Where, D_1 in equation (1) is calculated by:

$$D_1 = 2.191\times10^{-18}\frac{b g_g K_h}{\overline{m} h_p r_w} \qquad (2)$$

Equation (1) can be rewritten as the binomial:

$$p_e^2 - p_{wf}^2 = \frac{1.291\times10^{-3} T \overline{m} \overline{Z}}{K_h h_p} D_1 q_{sc1}^2 + \frac{1.291\times10^{-3} T \overline{m} \overline{Z}}{K_h h_p}\left(\ln\frac{r_e}{r_w} + S\right) q_{sc1} \qquad (3)$$

Where,

$$A_1 = \frac{1.291\times10^{-3} T \overline{m} \overline{Z}}{K_h h_p}\left(\ln\frac{r_e}{r_w} + S\right) \qquad (4)$$

$$B_1 = \frac{1.291\times10^{-3} T \overline{m} \overline{Z}}{K_h h_p} D_1 \qquad (5)$$

Productivity Formula of Unopened Gas Layer

Within the scope of the h-h_P in near wellbore area, the flow of gas is half spherical flow. Due to the formation anisotropy, horizontal or vertical permeability cannot simply be regarded as the effective permeability of gas flow. The effective permeability of spherical flow K_s [9] is calculated by:

$$K_s = \frac{3K_h K_v}{(K_h + 2K_v)} \tag{6}$$

Where, K_h is the horizontal effective permeability, K_v is the vertical effective permeability.

Without considering the bottom skin effect and non-Darcy flow, the production formula according to formula of hemispherical flow deduced by Chen Yuanqian [5] was:

$$q_{sc2} = \frac{Z_{sc}T_{sc}pK_s\left[y\,(p_e) - y\,(p_{wf})\right]}{p_{sc}T\left(\frac{1}{r_w} - \frac{1}{r_e}\right)} \tag{7}$$

Hemispherical productivity formula is represented by the pseudo-pressure in equation (7).

While using units of mines practical system and choosing P_{sc}=0.101325Mpa, T_{sc}=293K as standard condition the equation (7) can be transferred to:

$$q_{sc2} = \frac{774.6K_s\left[y\,(p_e) - y\,(p_{wf})\right]}{T\left(\frac{1}{r_w} - \frac{1}{r_e}\right)} \tag{8}$$

In formulas (8), the gas layer is considered as a homogeneous zone, whose permeability from the outer boundary to the bottom hole stays the same. And in the actual cases, due to the "pollution" of drilling and stimulation to gas layer, the permeability near the bottom changes, namely the skin effect. Within the scope that the radius is from r_a to r_w, considering the effect of skin factor S , formula (8) can be translated as:

$$y\,(p_e) - y\,(p_{wf}) = \frac{1.291\times10^{-3}q_{sc2}T}{K_s}\left[\frac{1}{r_w} - \frac{1}{r_e}\right] \tag{9}$$

The drop of Pseudo-pressure Δy_{skin} caused by the skin factor S in the equation (8) can be calculated by:

$$\begin{aligned}\Delta y_{skin} &= \frac{1.291\times10^{-3}q_{sc}T}{K_a}\left(\frac{1}{r_w} - \frac{1}{r_a}\right) - \frac{1.291\times10^{-3}q_{sc}T}{K_s}\left(\frac{1}{r_w} - \frac{1}{r_a}\right) \\ &= \frac{1.291\times10^{-3}q_{sc}T}{K_s r_w}\left(1 - \frac{r_w}{r_a}\right)\left(\frac{K_s}{K_a} - 1\right)\end{aligned} \tag{10}$$

Combining equation (9) and equation (10), the total drop of Pseudo-pressure is calculated by:

$$y\,(p_e) - y\,(p_{wf}) = \frac{1.291\times10^{-3}q_{sc2}T}{K_s r_w}\left[1 - \frac{r_w}{r_e} + \left(1 - \frac{r_w}{r_e}\right)\left(\frac{K_s}{K_a} - 1\right)\right] \tag{11}$$

In the literature [10] and production formula of the spherical flow derived by Zhang qinghui [6], the spherical flow skin factor was defined as $\left(\frac{1}{r_w} - \frac{1}{r_e}\right)\left(\frac{K_s}{K_a} - 1\right)$.Because the skin factor is a dimensionless quantity, so such a definition is clearly unreasonable. The author here makes the skin as $S = \left(1 - \frac{r_w}{r_e}\right)\left(\frac{K_s}{K_a} - 1\right)$, The formula (11) represented by pressure is calculate by:

$$q_{sc2} = \frac{774.6K_s r_w\left(p_e^2 - p_{wf}^2\right)}{T\overline{m}\overline{Z}\left(1 - \frac{r_w}{r_e} + S\right)} \tag{12}$$

The equation (7) can be transferred to

$$p_e^2 - p_{wf}^2 = \frac{1.291\times T\overline{m}\overline{Z}}{K_s r_w}\left(1 - \frac{r_w}{r_e} + S\right)q_{sc2} \tag{13}$$

For the thick gas reservoir, gas production rate is generally large. Gas velocity flowing into the bottom hole is high, and the flow state of the gas is non-Darcy flow. There, the non-Darcy flow must be taken into account in the new model.

For thick gas reservoirs, generally, the gas production is larger, and the flow of high velocity gas in the bottom is the non-Darcy. Additional pressure drop caused by non-Darcy flow must be considered. Assuming $r_e >> h$, $r_1 = h\text{-}h_P$, when $r_w < r < r_1$, the gas flow in the gas reservoir is the hemisphere flow and the non-Darcy seepage; When $r_1 < r < r_e$, the gas flow in the gas reservoir is the plane radial flow and Darcy seepage.

Through relevant experiments, Forchheimer had put forward the following quadratic equation to describe the non-Darcy flow

$$-\frac{dp}{dl} = \frac{mu}{K} + bru^2 \tag{14}$$

For hemisphere flow, the equation (14) can be expressed to

$$\frac{dp}{dr} = \frac{mu}{K_s} + bru^2 \tag{15}$$

Where， $b = \frac{7.644\times 10^{10}}{k_s^{1.5}}$， the unit of k_s is $10^{-3}mm^2$.

The second item on the right side of Formula (14) represent non-Darcy flow pressure drop, which is expressed by P_{nD}:

$$dp_{nD} = bru^2 dr \tag{16}$$

According to the following formula

$$r = \frac{M_{air} g_g p}{ZRT} \tag{17}$$

$$u = \frac{q}{2pr^2} \tag{18}$$

$$q = \frac{p_{sc}}{T_{sc}}\frac{ZT}{p}q_{sc2} \tag{19}$$

Combining equation(17)、(18)、(19)and equation(16), and choosing P_{sc}=0.101325*Mpa*,T_{sc}=293*K* as the standard condition，it can be calculated by：

$$\Delta p_{nD}^2 = 9.427\times10^{-22} b\, l_g \overline{Z}Tq_{sc2}^2\left(\frac{1}{r_w^3}-\frac{1}{r_1^3}\right) \qquad (20)$$

Equation（20）can be transferred to：

$$\Delta p_{nD}^2 = 1.291\times10^{-3}\frac{\overline{Z}\overline{m}Tq_{sc2}}{K_s r_w}D_2 q_{sc2} \qquad (21)$$

Where, D_2 is inertia or turbulence coefficient. In the formula derived by Zhang qinghui [6], D_2 is defined as

$$D_2 = 5.456\times10^{-19}\frac{Kbg_g}{\overline{m}}\left(\frac{1}{r_w^3}-\frac{1}{r_e^3}\right) \qquad (22)$$

In the formula (22), the coefficient calculation is wrong, and the item D_2q_{sc2} is not dimensionless in the formula (21). Here, the author defines the correct inertia factor D_2 as:

$$D_2 = 7.302\times10^{-19}\frac{K_s bg_g}{\overline{m}}\left(\frac{1}{r_w^2}-\frac{r_w}{r_1^3}\right) \qquad (23)$$

Incorporate additional pressure drop generated by non-Darcy flow in the formula (21) into the formula (13) ,it can be obtained：

$$p_1^2 - p_{wf}^2 = 1.291\times10^{-3}\frac{Z\overline{m}\overline{T}q_{sc2}}{K_s r_w}\left(1-\frac{r_w}{r_1}+S+D_2q_{sc2}\right) \qquad (24)$$

The formula (24) considering the non-Darcy flow of hemisphere is gas well productivity equation near wellbore. Where, S reflects the impact of changes in the permeability near the bottom and D_2q_{sc2} reflects the changes of the bottom flow, namely high-speed non-Darcy flow effects.

Radial flow in far wellbore area:

$$p_e^2 - p_1^2 = 1.291\times10^{-3}\frac{q_{sc2}T\overline{m}\overline{Z}}{K_h r_1}\ln\frac{r_e}{r_1} \qquad (25)$$

Combining equation (24) with equation (25), the gas capacity formula of unopened gas layer is calculated by

$$\begin{aligned} p_e^2 - p_{wf}^2 &= 1.291\times10^{-3}\frac{q_{sc2}T\overline{m}\overline{Z}}{K_s r_w}\left(1-\frac{r_w}{r_1}+S+D_2q_{sc2}\right) \\ &\quad +1.291\times10^{-3}\frac{q_{sc2}T\overline{m}\overline{Z}}{K_h r_1}\ln\frac{r_e}{r_1} \end{aligned} \qquad (26)$$

Equation (26) can be rewritten as the binomial:

$$\begin{aligned} p_e^2 - p_{wf}^2 &= 1.291\times10^{-3}\frac{T\overline{m}\overline{Z}}{K_s r_w}D_2q_{sc2}^2 \\ &\quad +1.291\times10^{-3}\overline{Z}\overline{m}T\left(\frac{1}{K_s r_w}\left(1-\frac{r_w}{r_1}+S\right)+\frac{1}{K_h r_1}\ln\frac{r_e}{r_1}\right)q_{sc2} \end{aligned} \qquad (27)$$

Where,

$$A_2 = 1.291\times10^{-3}\overline{Z}\overline{m}T\left(\frac{1}{K_s r_w}\left(1-\frac{r_w}{r_1}+S\right)+\frac{1}{K_h r_1}\ln\frac{r_e}{r_1}\right) \quad (28)$$

$$B_2 = 1.291\times10^{-3}\frac{T\overline{m}\overline{Z}}{K_s r_w}D_2 \quad (29)$$

According to the basic data of gas well and the properties of gas, the A_1, A_2, B_1 and B_2 can be calculated. Using the formula (3) and (27), q_{sc1}, q_{sc2} can be calculated respectively. The total output q_{sc} of gas well is calculated by

$$q_{sc} = q_{sc1} + q_{sc2} \quad (30)$$

When q_{wf}=0, the open flow potential of gas well can be calculated by the above equations.

Example Analysis

Taking five gas wells in a thick gas reservoir for instance, the AOF of gas wells can be calculate separately by above methods when considering skin factor or not. The results in table 1 as follow

Table1 Open-flow capacity calculation of gas well

Well name		N-1-1-DST1	N-1-1-DST2	N-1-2-DST1	N-1-3-DST2	N-1-4-DST1
layer		H3	H4	H5	H6	H7
Horizontal permeability, K (mD)		14.5	3.29	0.28	0.4	0.16
Vertical permeability, K (mD)		1.71	0.33	0.0383	0.075	0.025
thickness of the reservoir, h (m)		46.7	57.3	112.76	32	68
thickness of the perforated, h_p (m)		30	30	73	25.9	60
Wellbore radius ,r_w (m)		0.1015	0.1015	0.1015	0.1015	0.1015
Temperature, T (℃)		154	147	168	146.26	158
relative density of gas, γ_g		0.584	0.584	0.584	0.584	0.584
Skin factor ,S		4	6.7	34.6	6.8	-0.05
Supply radius, r_e (m)		500	500	500	500	500
original formation pressure ,P_i (MPa)		36.947	36.84	53.7	36.02	45.12
Gas viscosity,μ_g (mPa.s)		0.0236	0.0236	0.0276	0.0234	0.0257
Deviation coefficient, Z		1.0768	1.0726	1.2214	1.0658	1.1451
Open-flow capacity ($10^4 m^3/d$)	Test data interpretation	313.2	62.7	7.1	6.5	13.8
	Not considering the skin factor	499.778	115.078	36.170	11.778	14.066
	Consider the skin factor	339.671	64.280	7.127	6.525	14.173

Table1 illustrates the results considering skin factor are similar to the results of testing data interpretation. Deviation of calculating results without taking into account of skin factor is bigger. Results showed that the skin factor has a great influence on gas well production capacity. Therefore, in the process of gas well production calculation, the influence of the bottom skin effect can't be ignored.

Table2 The comparison between results of various methods

Well name	Open-flow capacity ($10^4m^3/d$)			
	Test data interpretation	Chen yuanqian method	Zhang qinhui method	Method presented in this paper
N-1-1-DST1	313.200	14.328	4.687	339.671
N-1-1-DST2	62.700	3.299	1.262	64.280
N-1-2-DST1	7.100	0.427	0.091	7.127
N-1-3-DST2	6.500	0.390	0.187	6.525
N-1-4-DST1	13.800	0.202	0.141	14.173

From table 2, for the great opening degree of the thick bottom-water gas reservoir, the previous models have not been applicable any more. The results compared to the actual situation have mistakes. The result calculated by the method presented in this paper is close to the actual result.

Taking N-1-1-DST2 Well for example, analyze the effect of open degree on gas well productivity. The results is shown in table 3 and fig. 2

Table 3 The influence of opening degree on production capacity

Opening degree （%）	considering the skin factor	Not considering the skin factor
43.6	53.584	95.955
52.4	64.280	115.078
61.1	74.976	134.202
69.8	85.672	153.327
78.5	96.368	172.451
87.3	107.064	191.575
96.0	117.759	210.698

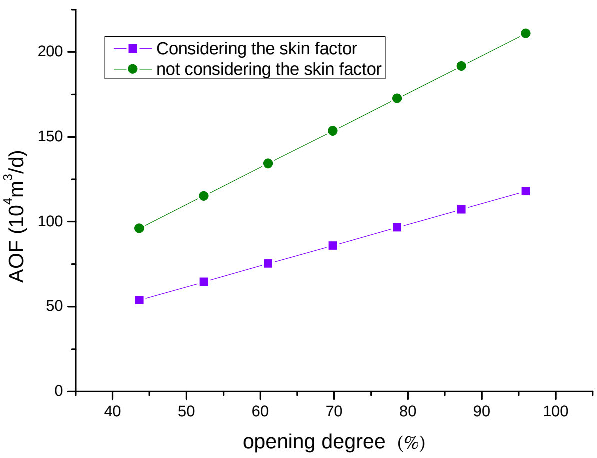

Fig.2 Relationship between Gas well open-flow capacity and open degree

From Fig. 2, AOF trends of gas well considering the skin effect or not are basically the same, all with the opening degree increases, AOF becomes large.

Conclusions

1）For exploitation of thick bottom water gas reservoir, in order to slow down and avoid the influence of bottom water coning on gas well productivity, usually only the upper part of the gas layer is perforated. Because its opening degree is bigger than conventional bottom water gas reservoir, the flow state can't be regard as half spherical flow in total gas layer as usually, but in perforated zone it is a planar radial flow and below perforated zone it is a combination of a hemispherical flow and a planar radial flow.

2）Skin factor and non-Darcy flow of gas has great influence on the gas well production capacity, therefore， which need to be considered when calculating the gas well production capacity near the bottom of skin effect and gas non-Darcy flow. Opening degree has a great impact on gas well productivity. With the increase of open degree, gas well production capacity raises. Because of the problem of bottom water coning, it is very important to choose the appropriate opening degree of the bottom water gas reservoir.

Explanation of symbols

p is pressure ，MPa；p_e is Formation pressure，MPa；p_{wf} is Bottom hole flowing pressure，MPa；p_1 is Radius r_1 pressure，MPa；$\overline{p}$ is Average pressure，MPa；$\Psi(p_e)$—Pseudo-pressure under pressure of p_e，$MPa^2/(mPa.s)$；$\Psi(p_{wf})$—Pseudo-pressure under pressure of p_{wf}，$MPa^2/(mPa.s)$；V is volume of gas，m^3；Z is gas compressibility factor；Z_{sc} is gas compressibility factor under standard condition；n is moles of gas；R is gas constant，$MPa.m^3/kmol.k$；m is mass of gas，t；M is molar mass of gas，kg/kmol；T is reservoir temperature，K；T_{sc} is temperature under standard condition，K；r is gas density under reservoir condition ,t/m^3；r_{sc} is gas density under standard condition，t/m^3；q_{sc} is production under standard condition，m^3/d；q is production under reservoir condition，m^3/d；A is area of hemispherical flow，m^2；r is radius of hemispherical flow，m；r_e is supply radius，m；r_w is Wellbore radius，m；r_a is radius of formation polluted，m；m_g is gas viscosity，mPa.s；K is effective permeability，$10^{-3} mm^2$；K_h is horizontal effective permeability，$10^{-3} mm^2$；K_v is vertical effective permeability，$10^{-3} mm^2$；K_s is Spherical flow effective permeability，$10^{-3} mm^2$；K_a is effective permeability of gas after pollution，$10^{-3} mm^2$；S is skin factor；b is Speed coefficient，m^{-1}；u is velocity of gas phase，m/s；g_g is relative density of gas.

References

[1]Song Zhaojie, Li Xiangfang, Li Zhiping,et al.A Model for Calculating Critical Production Rates of Water Coning with Consideration of Non-Darcy Flow[J].Acta Petrolei Sinica, 2012, 33(1): 106-111.

[2]Kabir C S. Predicting gas well performance coning water in bottom-water-drive reservoirs[C]//SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1983.

[3]Mingxuan Y G L J J, Dehua L. Production Mechanism and Development Tactics on Sandstone Reservoirs with Bottom Water [J]. Acta Petrolei Sinica, 1997, 2.

[4]Jin L, Wojtanowicz A K, Hughes R G. An Analytical Model for Water Coning Control Installation in Reservoir With Bottom water[J]. Journal of Canadian Petroleum Technology, 2010, 49(05): 65-70.

[5]Chen Yuanqian, Sunbing，Jiang Fengguang, et al.Derivation and Application of Semi-Spherical Flow Production Formula of gas well, 2009, 18(03):1-4, 75.

[6]Zhang Qinghui, Li Xiangfang,Yuan Haiju, et al.Deliverability equation derivation of semi-spherical flow gas wells considering non-Darcy flow[J].Reservoir Evaluation and Development,2011,1(05):24-28.

[7]Luo yinfu,Huang Bingguang,Yi ga,et al.Well Test Analysis of Gas Well Production at Constant Pressure Accounting for High Velocity Non-Darcy Flow[J].Jouunnal of Southwest Petroleum University(Science&Technology Edition) , 2008, 30(2): 91-93.

[8]Li Shilun.Natural gas engineering[M].Beijing:Petroleum Industry Press, 2010:88-89.

[9]Zhu Yadong. Well Test Analysis Method of Spherical Flow[J].Well Teseting, 1990 (3): 26-33.

[10]Wang Xiaodong, Zhang Qibin, Zou Yanhua.Skin Factor and Flow Pattern[J].Well Teseting, 2005, 14(2): 1-3.