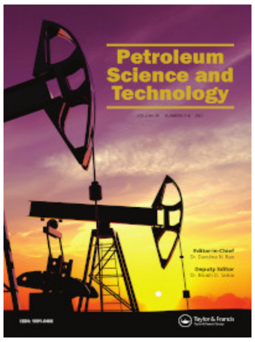

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Absolute open flow (AOF) potential evaluation for watered-out gas wells in water-drive gas reservoir

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ABSTRACT

This paper presents a gas-water two-phaseLaminar-Inertial-Turbulent (LIT) flow equation for watered-out gas wells, which can be solved through the incorporation of daily production, gas-water relative permeability and PVT data, and then Q_{AOF} and formation factor (*Kh)* are obtained. Field case study in Long Wang Miao (LWM) water-drive gas reservoir shows that for watered-out gas wells, the single-phase LIT equation can result in overestimation of Q_{AOF} by 30–80%. Water invasion performance can be relieved after reducing the production rate of watered-out gas wells, and water invasion behavior before breakthrough can be diagnosed with the decline trend of *Kh* values.

KEYWORDS

absolute open flow potential; gas-water two-phase flow; laminar-inertial-turbulent equation; watered-out gas wells; water invasion diagnosis

1. Introduction

More than half of the gas reservoirs have sizable edge or bottom aquifer (Song 2011; Hu 2013; Ogolo, Isebor, and Onyekonwu 2014; Al-Fatlawi 2018), during depleted exploitation, the aquifer water will be compressed and encroach into gas reservoirs and then break into gas wells, which severely reduces well deliverability and causes significant loss of gas EUR. Literatures have shown that compared to single gas phase flow in volumetric reservoirs, up to 20%–30% of the gas recovery will be reduced due to the gas-water two phase flow for water encroached gas reservoirs (Givens 1968; Firoozabadi, Olsen, and Golf-Racht 1987; Charles, Tracy, and Farrar 1999; Ahmed and McKinney 2005). For these water flooded gas reservoirs, the management, observation, and production optimization for watered-out gas wells become one of the major concerns in reservoir engineering. Better understanding of well deliverability after water invasion for these

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wells are crucial for proper control of gas production rate in minimizing the impact of water and maintaining stable and continuous gas flowing.

In terms of the evaluation on the wells deliverability, previous studies have presented a great number of mathematical models or equations to calculate the wells productivity accurately (Brown 1992; Wiggins et al. 1994; Ottba and Al-Jawad 2006). Since it is time consuming and expensive to determine the wells deliverability by conducting multi-point test, therefore, a simplified procedure that only uses single-point test for deliverability calculation of gas wells was presented by Mishra and Caudle (1984), in which the analytical solution of real gas flow under stabilized conditions is used. However, it is difficult to solve the pseudo-pressure (Al-Hussainy, Ramey, and Crawford 1966; Al-Hussainy and Ramey 1966), then Chase, Marietta, and Anthony (1988) offered a simplification technique to predict the fractured or unfractured gas well deliverability, in which a range of pressure values was defined over which pressure-squares can be substituted for pseudo-pressure. To determine the parameters used in the calculation of deliverability precisely, Chase and Alkandari (1993) described a method to predict the deliverability for hydraulically fractured gas wells that required only pressure build-up or draw down test data. For unfractured gas wells and horizontal wells, Chase (2002) converted the apparent skin factor to an equivalent ratio and then developed dimensionless Inflow Performance Relation (IPR) curves model to estimate the stabilized deliverability using build-up or draw-down test data. During single–rate fall-off or build-up test, when turbulence factor is unavailable, the mechanical skin factor is inaccurate, so Aminian et al. (2007) introduced the concept of reservoir-specific β-factor to determine the mechanical skin factor and deliverability equation coefficients. Recently, for specific reservoirs, such as gas-condensate, sour, volcanic, and abnormal pressure gas reservoir, the researchers deduce novel deliverability equations, in which the presented models consider the effects of a lot of factors, for instance, gas-oil relative permeability, capillary number, non-Darcy flow, sulfur deposition, pseudo-steady or unsteady seepage conditions, and threshold pressure drop (Mazloom and Rashidi 2006; Chowdhury et al. 2008; Xu et al. 2008; Sadeghi Boogar and Masihi 2010; Shi, Li, and Shi 2010; Shi et al. 2013; Hu et al. 2014; Wu et al. 2014). For general cases, Al-Zuhair (2009) used analytical solutions to diffusivity equations for real gas flow under stabilized or pseudo-steady-state flow conditions and a wide range of rock and fluid properties to generate an empirical correlation to calculate gas well deliverability. For some complex well types, such as horizontal and hydraulically-fractured horizontal wells, the robust models to predict IPR curves by using single-point flow test are introduced (Chase and Steffy 2004; Mohamed and Abdalla 2020).

Apart from the evaluation of wells deliverability for single-phase flow, in some circumstances, two-phase flow always occurs in porous media or wellbore. Many literatures present models for predict gas-oil two-phase flow. In order to predict the IPR curves for gas-oil two-phase flow condition, the modified Vogel's correlations using characteristics flow behavior for two-phase IPR curves for horizontal and multilateral wells are presented, which can be used to calculate AOF potential (Kamkom and Zhu 2005; Zhu and Kamkom 2005; Ilk, Camacho Velazquez, and Blasingame 2007). In addition, for horizontal two phase IPR curves, Jabbar and AlNuaim (2013) proposed a new correlation to estimate well performance based on the regression of the coefficients for Harrison equation. Since the presented two-phase models usually assumes steady or pseudo-steady flow, which many wells may never truly reach, therefore, Sousa, Garcia, and Waltrich (2017) proposed dynamic IPR for transient two-phase flow, which accounts for the flow dynamics near the wellbore region.

Through the above comprehensive reviews on the deliverability evaluation for single-phase and two-phase flow condition, we can see that the studies mainly focus on the estimation of deliverability for single-phase. For two-phase flow, the developed models can predict the wells productivity very well during gas-oil two-phase flow, while it lacks the description for water-gas two phase flow in watered out gas reservoir. Hence, it is essential to propose mathematical model to evaluate the deliverability for watered-out gas wells. In this paper, gas-water two-phase LIT flow equation for watered-out gas wells is presented. Field application in LWM gas reservoir shows that two-phase LIT flow equation can predict Q_{AOF} accurately compared with the single phase LIT flow equation. Additionally, the approach of water invasion performance diagnosis for gas wells before water breakthrough is also proposed.

2. Traditional gas well deliverability estimation

For gas well deliverability evaluation, traditional Laminar-Inertial-Turbulent (LIT) approaches with flow-after-flow tests are usually employed to determine AOF potential of gas wells (Q_{AOF}). For a radial, homogenous gas reservoir, when pseudo-steady state is reached, the well flowing equation can be given by Eq. (1) in pseudo-pressure form (Ahmed 2010):

$$\psi_R - \psi_{wf} = 12.74\frac{q_g T}{Kh}\left(\ln\frac{r_e}{r_w} - \frac{3}{4} + S_a\right) \tag{1}$$

Where ψ_R is defined as pseudo-pressure at reservoir pressure p_R, and ψ_{wf} as pseudo-pressure at bottom hole flowing pressure p_{wf}.

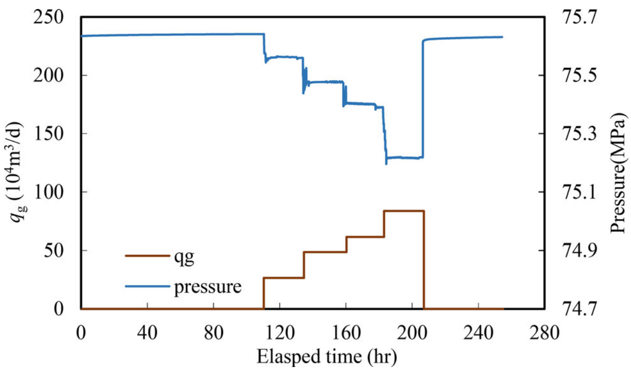

Figure 1. Gas well flow rate and pressure in flowing test.

$$\psi_R = \int_{p_0}^{p_R} \frac{2p}{\mu z} dp$$

$$\psi_{wf} = \int_{p_0}^{p_{wf}} \frac{2p}{\mu z} dp$$

Equation (1) can be simplified as:

$$\psi_R - \psi_{wf} = Aq_g + Bq_g^2 \tag{2}$$

Where A and B are defined by Eqs. (3) and (4).

$$A = \frac{12.74T}{Kh}\left(\ln\frac{0.472r_e}{r_w} + S\right) \tag{3}$$

$$B = \frac{12.74T}{Kh}D \tag{4}$$

The Open Flow Potential of gas (Q_{AOF}) can be calculated with Eq. (5).

$$Q_{AOF} = \frac{-A + \sqrt{A^2 + 4B\psi_R}}{2B} \tag{5}$$

In field application, a series of flow tests are conducted usually with four different flow rates (as shown in Figure 1) and p_{wf} under each flow rate will be gauged. Then $(\Psi_R\text{-}\Psi_{wf})/q_g$ vs. q_g will be plotted in Cartesian coordinates to make linear regression (as shown in Figure 2) and calculate coefficient A and B in Eq. (2) with which the well's Inflow Performance Relationship (IPR) curve can be plotted as Figure 3. The Q_{AOF} can be calculated either with Eq. (5) or by extrapolating the IPR curve to the X-axis in Figure 3.

However, for watered-out gas wells, the above traditional approach for deliverability prediction has two drawbacks: first, the fluctuation of flow rates during flow test can aggravate the invasion of water, and second, the LIT equation, derived from single gas phase flowing theory, will

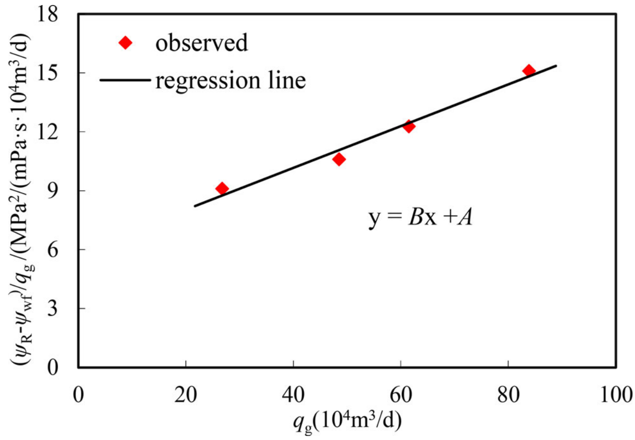

Figure 2. Gas well deliverability curve.

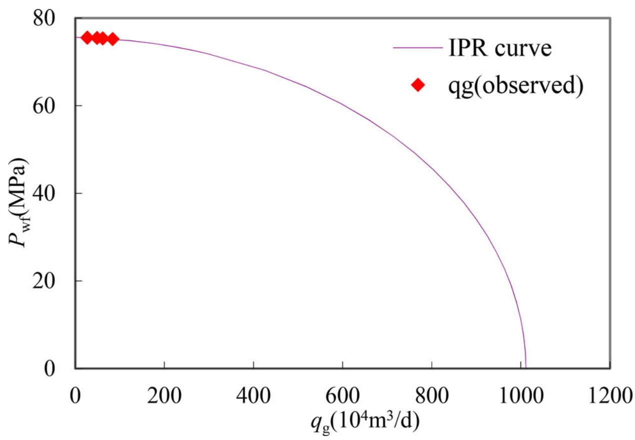

Figure 3. Gas well IPR curve.

overestimate Q_{AOF}. Therefore, to obtain accurate Q_{AOF}, in this paper, two-phase LIT flow equations are established, and the methodologies of predicting Q_{AOF} for watered-out gas wells through the utilization of daily production data are given, thus, fluctuations caused by flow tests can be avoided.

3. Gas-water two-phase LIT equation establishment

For a homogenous reservoir with gas and water two-phase flow, based on Darcy's Law, the flow rate of each phase can be described as:

$$\vec{v}_g = -\frac{KK_{rg}}{\mu_g}\nabla p \tag{6}$$

$$\vec{v}_w = -\frac{KK_{rw}}{\mu_w}\nabla p \tag{7}$$

Substitute the transport equation (Eqs. (6) and (7)) and equation of state (Eq. (8)) into continuity equation (Eq. (9)), the flow equation for each phase can be derived, as shown in Eq. (10).

$$C_j = \frac{1}{\rho_j}\frac{\partial \rho_j}{\partial p}, \quad C_\mathrm{f} = \frac{1}{\varphi}\frac{\partial \varphi}{\partial p} \tag{8}$$

$$\nabla\left(\rho_j \vec{v_j}\right) = -\frac{\partial}{\partial t}(\varphi \rho_j) \tag{9}$$

$$\nabla\left(\rho_j \frac{K_{\mathrm{r}j}}{\mu_j}\nabla p\right) = -\frac{\varphi \rho_j}{K}(C_j + C_\mathrm{f})\frac{\partial p}{\partial t} \tag{10}$$

In Eqs. (8) and (10), j can be "g" or "w," which represents gas or water phase. To calculate Q_{AOF} of water-out gas wells, the two-phase pseudo-pressure ψ' is defined as:

$$\psi' = \int_{p_0}^{p}\left(\rho_\mathrm{w}\frac{K_\mathrm{rw}}{\mu_\mathrm{w}} + \rho_\mathrm{g}\frac{K_\mathrm{rg}}{\mu_\mathrm{g}}\right)dp \tag{11}$$

To solve Eq. (10), the initial, inner, and outer boundary condition should be defined.

The initial conditions can be expressed by:

$$\psi'|_{t=0} = \psi'_\mathrm{R} \tag{12}$$

As the gas well is assumed to produce with a constant rate, and the outer boundary is closed, hence, the inner and outer boundary conditions can be given by Eq. (13) and Eq. (14), respectively:

$$r\frac{\partial \psi'}{\partial r}\bigg|_{r=r_\mathrm{w}} = \frac{q_\mathrm{t}}{2\pi K h} \tag{13}$$

$$r\frac{\partial \psi'}{\partial r}\bigg|_{r=r_\mathrm{e}} = 0 \tag{14}$$

For wells with constant production rate, in pseudo-steady state flow, the solution of Eq. (10) can be obtained as Eq. (15) (seen Appendix A).

$$\psi'_\mathrm{R} - \psi'_\mathrm{wf} = \frac{1.842 q_\mathrm{t}}{Kh}\left(\ln\frac{0.472 r_\mathrm{e}}{r_\mathrm{w}} + S + Dq_\mathrm{t}\right) \tag{15}$$

In Eqs. (13) and (15), q_t is the total mass flow rate and is defined as:

$$q_\mathrm{t} = q_\mathrm{g}\rho_\mathrm{gsc} + q_\mathrm{w}\rho_\mathrm{wsc} = q_\mathrm{g}(\rho_\mathrm{gsc} + R_\mathrm{wg}\rho_\mathrm{wsc}) \tag{16}$$

Where:

$$R_\mathrm{wg} = \frac{q_\mathrm{w}}{q_\mathrm{g}}$$

Substituting Eq. (16) into Eq. (15), a simplified form of deliverability equation for water-out gas wells can be established as Eq. (17), which has identical form with Eq. (2):

$$\psi'_{\mathrm{R}} - \psi'_{\mathrm{wf}} = A' q_{\mathrm{g}} + B' q_{\mathrm{g}}^2 \tag{17}$$

The coefficient A', B' are given in Eq. (18) and Eq. (19), respectively.

$$A' = \frac{1.842(\rho_{\mathrm{gsc}} + R_{\mathrm{wg}}\rho_{\mathrm{wsc}})}{Kh}\left(\ln\frac{0.472r_{\mathrm{e}}}{r_{\mathrm{w}}} + S\right) \tag{18}$$

$$B' = \frac{1.842(\rho_{\mathrm{gsc}} + R_{\mathrm{wg}}\rho_{\mathrm{wsc}})^2}{Kh}D \tag{19}$$

Equation (17) is the gas-water two-phase LIT flow equation, and when the values of A' and B' are determined, the Open Flow Potential of gas for the watered-out gas well can be calculated with Eq. (20).

$$Q'_{\mathrm{AOF}} = \frac{-A' + \sqrt{A'^2 + 4B'\psi'_{\mathrm{R}}}}{2B'} \tag{20}$$

The most import part for the two-phase LIT flow equation is the introduction of two-phase pseudo-pressure ψ, which incorporates the gas-water relative permeability and PVT data of each phase. The method for pseudo-pressure calculation is given in Appendix B.

4. Watered-out gas well deliverability analysis with two-phase LIT equation

4.1. Deliverability determination with daily production data

For watered-out gas wells, few deliverability tests are conducted because the rate fluctuation during flow test will disturb the flow in the reservoir and aggravate water invasion. In this section, the methodologies to evaluate well deliverability with daily production data are presented.

To solve the watered-out gas well deliverability conveniently, A'' and B'' are introduced in Eq. (21) and Eq. (22), respectively.

$$A'' = 1.842(\rho_{\mathrm{gsc}} + R_{\mathrm{wg}}\rho_{\mathrm{wsc}})\left(\ln\frac{0.472r_{\mathrm{e}}}{r_{\mathrm{w}}} + S\right) \tag{21}$$

$$B'' = 1.842(\rho_{\mathrm{gsc}} + R_{\mathrm{wg}}\rho_{\mathrm{wsc}})^2 D \tag{22}$$

From definition, the correlations between A'' and A', and B'' and B' can be expressed in Eq. (23) and Eq. (24), respectively.

$$A' = \frac{A''}{Kh} \tag{23}$$

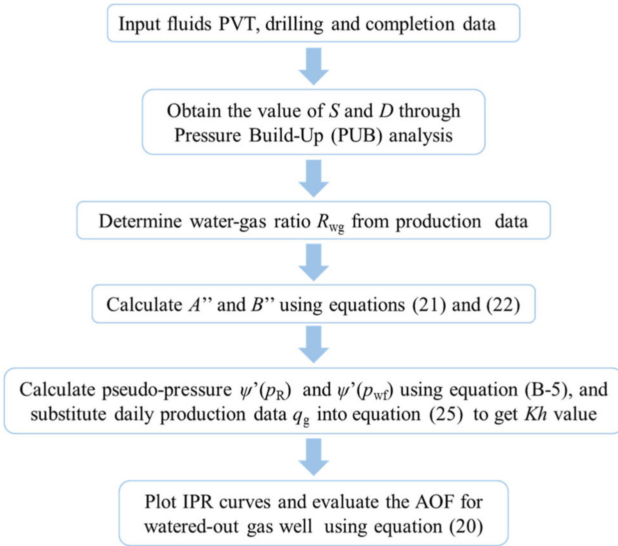

Figure 4. Procedure to solve the established two-phase LIT equation.

$$B' = \frac{B''}{Kh} \tag{24}$$

Then, Eq. (17) can be written as:

$$\psi'_R - \psi'_{wf} = \frac{A''}{Kh} q_g + \frac{B''}{Kh} q_g^2 \tag{25}$$

From Eqs. (21) and (22), it can be seen that, the values of A'' and B'' can be quantified explicitly since the parameters ρ_{gsc}, ρ_{wsc}, r_e, and r_w can be given easily with PVT data, drilling and completion data, the S and D values can be obtained through Pressure Build-Up (PBU) analysis, and the producing water-gas ratio R_{wg} can be determined from production data. When A'' and B'' are determined, the Kh value can be calculated implicitly by substituting daily production data $\psi'_R(p_R)$, $\psi'_{wf}(p_{wf})$ and q_g into Eq. (25), and then the two-phase LIT equation coefficients A' and B' can be calculated with Eq. (23) and Eq. (24), respectively. When the coefficients are given, IPR curves can be established with Eq. (17) and Q'_{AOF} can be predicted by Eq. (20). The above solution process for the proposed methodology can be represented with the following flowchart, as shown in Figure 4.

Here is a field example to show the procedure of deliverability analysis with production data. The initial reservoir pressure and temperature are 76 MPa and 140 °C, respectively. The density of gas and water at standard conditions, ρ_{gsc} and ρ_{wsc}, are 0.70 kg/m^3 and 1000 kg/m^3, respectively. From the inter-well spacing, the well drainage radius r_e is about 1500 m and default value of r_w is 0.1 m. Based on PBU analysis, the skin factor S is

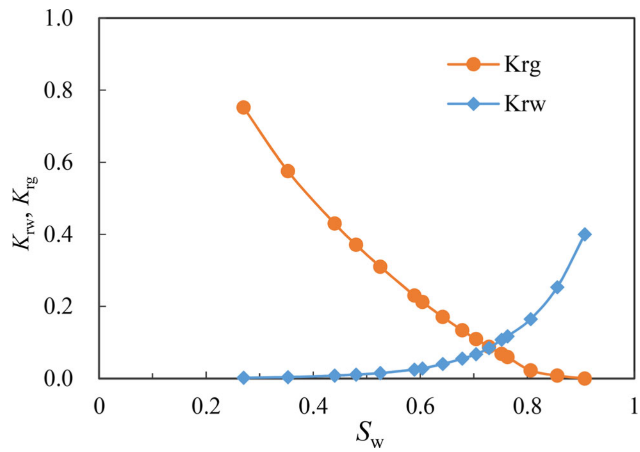

Figure 5. Gas-water relative permeability curves.

−3 and non-Darcy flow coefficient D is $4 \times 10^{-6}(m^3/d)^{-1}$ or $5.7 \times 10^{-6}(kg/d)^{-1}$. The watered-out gas well is producing with gas production rate $q_{gsc} = 30 \times 10^4 m^3/d$ and water production rate $q_{wsc} = 100 m^3/d$ at well bottom-hole flowing pressure $p_{wf} = 59.30$ MPa, and the current reservoir pressure is depleted to $p_R = 60.06$ MPa. Figure 5 presents the lab tested gas–water relative permeability curve. Figure 6 is the relationship curve between two-phase pseudo-pressure and pressure, in which the pseudo-pressure at reservoir average pressure p_R and well bottom-hole pressure p_{wf} can be determined.

Substituting the static parameters ρ_{gsc}, ρ_{wsc}, r_e, r_w, R_{wg}, S, and D into Eqs. (21) and (22), and the values of A'' and B'' are quantified as 11.2514 and 7.6675×10^{-6}, respectively. And Kh value is given as 914.3mD·m after substituting flowing data $\psi'_R(p_R)$, $\psi'_{wf}(p_{wf})$ and q_g into Eq. (25). Based on Eqs. (23) and (24), A' and B' are determined as $A' = 0.012306$ and $B' = 8.3862 \times 10^{-9}$. The two-phase LIT equation can be written as:

$$\psi'_R - \psi'_{wf} = 0.012306 q_g + 8.3862 \times 10^{-9} q_g^2 \quad (26)$$

From Eq. (26), the gas AOF for two phase flow is calculated as $478.3 \times 10^4 m^3/d$. When the water phase is neglected by assuming $R_{wg} = 0$ and $K_{rw} = 0$, the gas AOF is given as $545.9 \times 10^4 m^3/d$. Through the comparison of Q_{AOF} values for two phase flow and single gas phase flow, we can see that the Q_{AOF} value for single gas flow is 14% higher than the case with consideration of water-gas flow effect.

4.2. Influence of water-gas ratio on watered-out gas well deliverability

Through the comparison of deliverability for the cases with and without consideration of two-phase flow, we can see that water production or

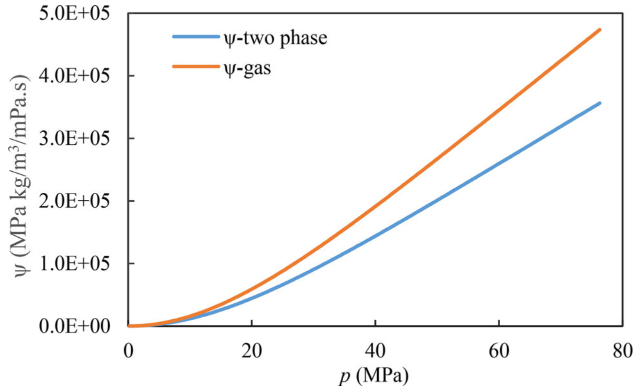

Figure 6. Pseudo-pressure vs. pressure.

water-gas ratio has significant effect on the deliverability. To evaluate water production on watered-out gas well deliverability directly, a series of water-gas ratio (R_{wg}) values are set reasonably while other parameters remain the same as in the field case of Section 4.1. Following the same procedure as introduced in Section 4.1, the $\psi'_R(p_R)$, $\psi'_{wf}(p_{wf})$, A', B' and LIT equation at different R_{wg} are established, and the IPR curves are plotted in Figure 7.

It can be seen from Figure 7 that with the increase of R_{wg}, the deliverability of gas well is decreasing, which indicates that for gas wells after water breakthrough, deliverability will be overestimated if single gas phase LIT equation is used. For instance, for case without consideration of water production, the gas well deliverability is 32.5% larger than the case with water-gas ratio 1/600. However, as the rise of water-gas ratio, though Q_{AOF} decreases continuously, the gaps of Q_{AOF} for cases with various water-gas ratio reduces, which demonstrates that the influence of water-gas ratio on Q_{AOF} minimize. In practice, when single gas phase LIT equation is used to obtain the deliverability of watered-out gas well, which leads to the optimistic evaluation of gas well flow capacity, and then causes higher proration with larger sandface drawdown pressure, and indeed aggravates water invasion.

5. Field application

5.1. Gas well deliverability evaluation before and after water breakthrough

Based on the methods proposed in Section 4, Gas well Q_{AOF} (with and without incorporating water phase) can be calculated with daily flowing data, and thus the productivity decline trends of gas wells can be analyzed easily. Figure 8 shows the production profile and deliverability decline trend for well MX8 in LWM gas reservoir before and after water breakthrough, the rapid decrease of Q_{AOF} can be clearly viewed after water

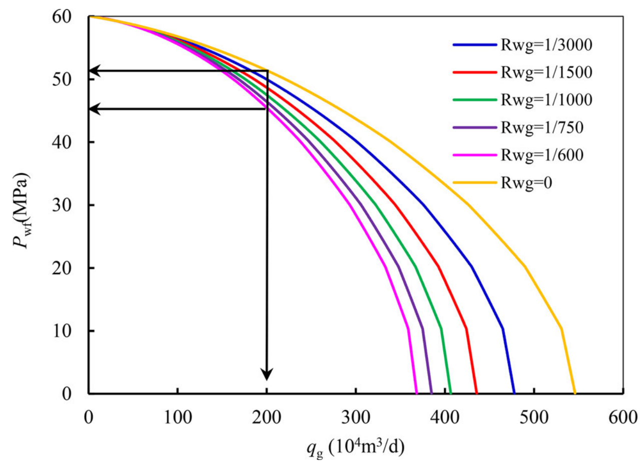

Figure 7. IPR curves for cases with different water-gas ratio.

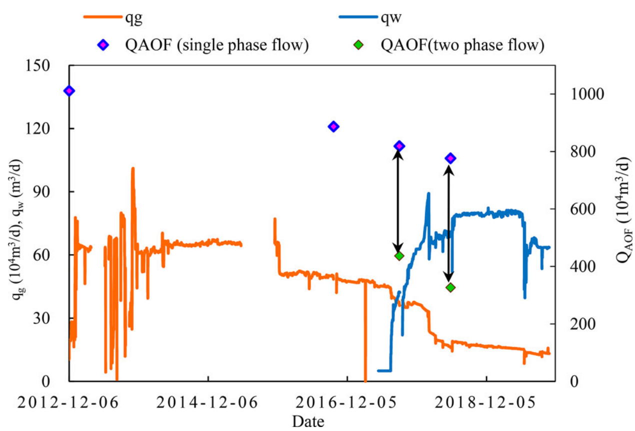

Figure 8. Production history and Q_{AOF} in well MX8.

breakthrough by using the gas-water two phase LIT method. IPR curves in Figure 9 for this well shows that compared with initial AOF data, in May 2018, seriously influenced by the water production, the well deliverability had decreased by 67.5%, the utilization of single phase LIT equation can result in overestimation of Q_{AOF} by 30–80%.

5.2. Well production optimization after water breakthrough

Productivity analysis for water-out gas wells in LWM gas reservoir suggests that, based on two-phase LIT equation, current drawdown pressures are high above the limit, and flow rates should be lowered. For watered-out gas wells MX11 and MX205, the gas production rates are adjusted from $60 \times 10^4 m^3/d$ to $30 \times 10^4 m^3/d$. It can be seen from Figure 10 that after the reduction of gas production rate, the rapid rising trends of water production rate for these two wells are restrained, and long and stable gas

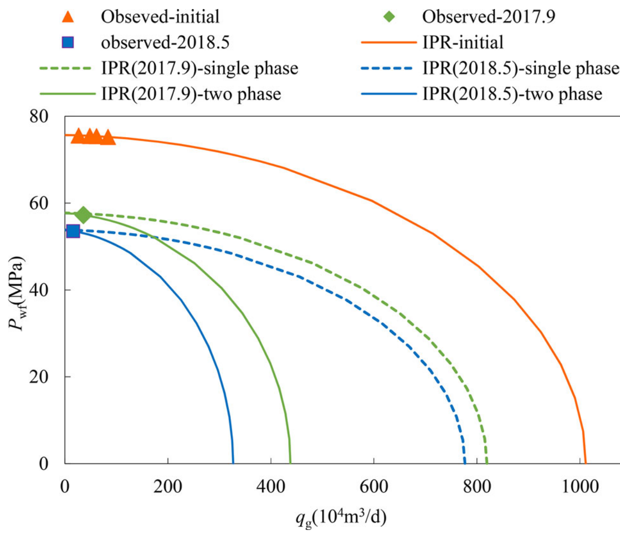

Figure 9. IPR curves with single phase and two phase flow in well MX8.

production rates are maintained, which indicates satisfactory effects of water invasion inhabitation after production optimization. The above taken measures in LWM gas reservoir is meaningful for gas reservoir with edge or bottom aquifer, while a large amount of water is produced from gas wells, to relieve the influences of water production on performance, gas production rate for these wells should be lowered reasonably as soon as possible. The earlier the measures are taken, the more gas it can be recovered.

5.3. Water invasion diagnosis with daily flowing data for wells before water breakthrough

Theoretically, the encroachment of water into gas reservoir can impair underground gas mobility and cause reduction of *Kh* within well drainage area. Therefore, the methodology presented in Section 4.1 to calculate *Kh* with daily flowing data can also be used for water invasion diagnosis before water breakthrough into gas wells. Before water breakthrough, the two-phase LIT equation given in Eq. (17) can be simplified to calculate both Q_{AOF} and *Kh* for single phase gas flow. Figures 11 and 12, and Table 1 present the calculated *Kh* values for wells with high water invasion risk in LWM gas reservoir, and the date of water breakthrough is also given. Before the moment of water breakthrough, the clear decline trend of *Kh* value can be observed in these wells, which shows the encroachment of water into well drainage area. This methodology provides an efficient and cost effective way for water invasion diagnosis. In practice, for wells with potential risk of water-out, when the calculated *Kh* values decrease with the

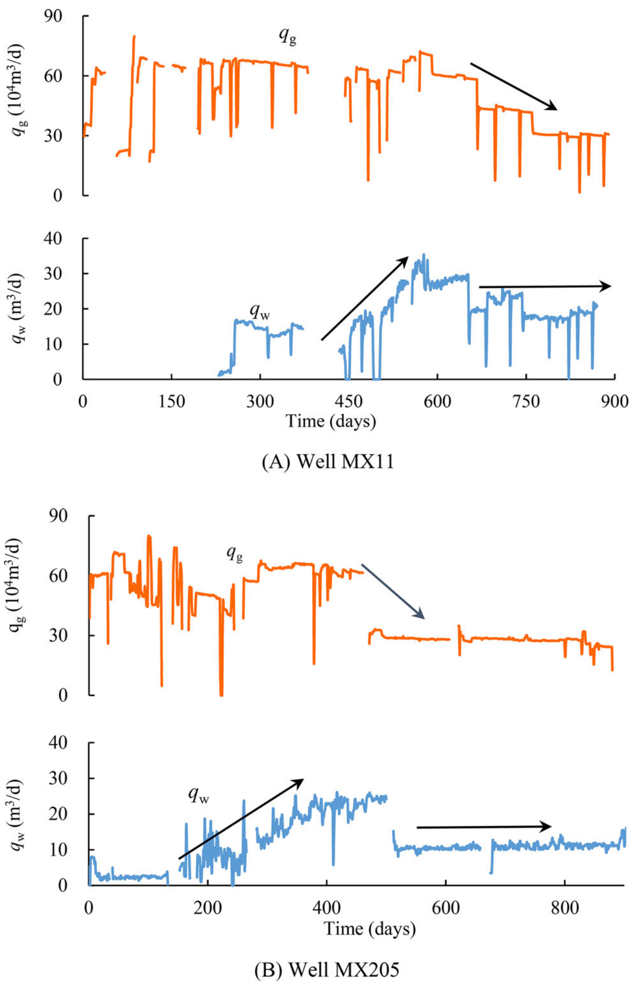

Figure 10. Water flow rate before and after production optimization in watered-out gas wells.

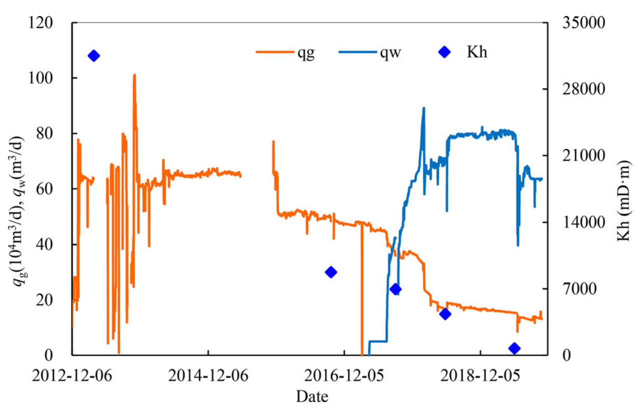

Figure 11. Production profile and *Kh* decline trend for MX8.

Table 1. *Kh* decline trend for high risk of water invasion wells.

Well ID	Date (YYYY/MM/DD)	q_g ($10^4 m^3/d$)	P_R (MPa)	P_{wf} (MPa)	Q_{AOF} ($10^4 m^3/d$)	*Kh* (mD·m)	Date of water breakthrough (YYYY/MM/DD)
MX8	2013/04/03	48.5	75.64	75.47	1052	31515	2017/7/21
	2016/09/24	44.4	63.97	63.48	523	8763	
	2017/09/05	36.0	57.718	57.257	437	6969	
	2018/05/30	16.0	53.82	53.56	326	4352	
	2019/06/05	15.3	48.3	46.84	112	741	
MX8-12-X1	2017/05/19	80.1	64.76	61.92	360	359	2020/1/22
	2018/05/4	64.9	60.12	57.87	333	338	
	2019/08/21	63.9	54.49	52.06	298	307	
MX9-3-X1	2015/09/9	81.5	70.05	69.63	915	2674	2018/12/30
	2016/04/13	84.5	67.31	66.77	814	2231	
	2018/06/10	57.0	59.07	58.70	771	2121	
	2019/07/02	34	56.74	53.88	147	106.9	

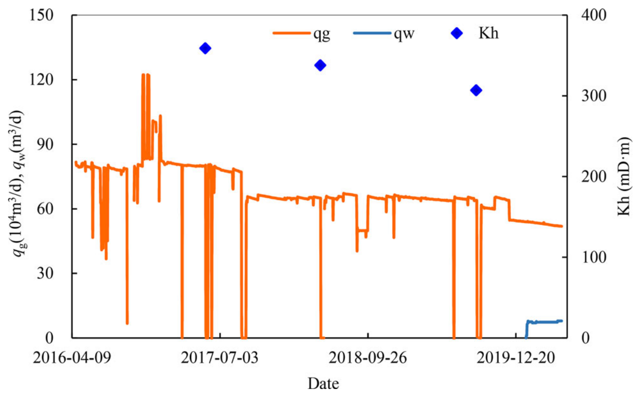

Figure 12. Production profile and *Kh* decline trend for MX8-12-X1.

extension of production time, to avoid the rapid water invasion and delay the time of water breakthrough, the production rate of these wells should be lowered in advance.

6. Conclusion

1. A gas-water two-phase LIT equation is established by incorporating the relative permeability and PVT data of both phases in the Pseudo-pressure term and total flow rate in the rate term, in which the effects of water invasion on gas deliverability is included and the overestimation of watered-out gas well deliverability by using single gas phase LIT method is avoided.
2. The approach to analyze watered-out gas well deliverability with daily production data is given, in which coefficients of the two-phase LIT equation are defined, both Q_{AOF} and *Kh* are calculated, and IPR curve is plotted. Compared with traditional deliverability tests in defining LIT

equation, the proposed method is efficient and avoids flow fluctuation during deliverability tests.

3. Sensitivity analysis of the two-phase LIT equation shows that, the gas deliverability of watered-out wells are highly influenced by water production rate or R_{wg}. With the increase of R_{wg}, the deliverability of gas well is decreasing. This indicates that for gas wells after water breakthrough, deliverabilities will be overestimated if single gas phase LIT equation are used, and furthermore, the optimistic evaluation of gas well flow capacity will cause higher proration with larger sandface drawdown pressure, and aggravate water invasion.
4. Field application in LWM gas reservoir shows that Q_{AOF} can be overestimated by 30–80% for watered-out gas wells when single gas phase LIT equation is used. After the optimization of production for these wells, satisfactory effect of water invasion inhabitation can be seen in practice. The methodology of analyzing the variation law of *Kh* values provides an efficient and cost effective way for water invasion diagnosis before water breakthrough into gas wells.

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Appendix A. Derivation of two-phase flow equation in pseudo-steady state

When the fluids flow reaches pseudo-steady state, then the variation of pressure with time keeps constant, and the gas production is equal to the volume of fluids caused by the compressibility of rock and fluids.

$$\frac{\partial p}{\partial t} = \text{constant} \tag{A1}$$

$$C_t = -\frac{1}{V}\frac{dV}{dp}, \quad C_t = C_j + C_f \tag{A2}$$

The Eq. (A2) can be transformed into:

$$C_t V dp = -dV \tag{A3}$$

Through the derivative of time t on both sides of Eq. (A3):

$$C_t V \frac{dp}{dt} = -\frac{dV}{dt} = q_j \tag{A4}$$

For radial gas reservoir, the pore volume can be given by

$$V = \pi r_e^2 h \phi \tag{A5}$$

Substituting Eq. (A5) into Eq. (A4), we can obtain:

$$\frac{dp}{dt} = \frac{q_j}{C_t \pi r_e^2 h \varphi} \tag{A6}$$

Then, substituting Eq. (A6) into Eq. (10), and the two-phase flow equation for radial flow can be obtained:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho_j \frac{K_{rj}}{\mu_j}\frac{\partial p}{\partial r}\right) = -\frac{\rho_j q_j}{\pi K r_e^2 h} \tag{A7}$$

In Eq. (A7), j can be “g” or “w,” which represents gas or water phase. We can plus these two equations for water and gas phases:

$$\frac{1}{r}\frac{\partial}{\partial r}\left[\left(\rho_g \frac{K_{rg}}{\mu_g} + \rho_w \frac{K_{rw}}{\mu_w}\right) r \frac{\partial p}{\partial r}\right] = -\frac{\rho_g q_g + \rho_w q_w}{\pi K r_e^2 h} \tag{A8}$$

According to the definition of two-phase pseudo-pressure and total mass flow rate in Eqs. (11) and (16), the Equation can be rewritten:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial \psi'}{\partial r}\right) = -\frac{q_t}{\pi K r_e^2 h} \tag{A9}$$

Integrating on the both sides of Eq. (A9) from r_e to r yields:

$$\left(r\frac{\partial\psi'}{\partial r}\right)\bigg|_{r_e} - \left(r\frac{\partial\psi'}{\partial r}\right)\bigg|_{r} = -\frac{q_t}{2\pi K r_e^2 h}\left(r_e^2 - r^2\right) \tag{A10}$$

Through the combination of the outer boundary condition in Eq. (14), the Eq. (A10) can be simplified as:

$$0 - \left(r\frac{\partial\psi'}{\partial r}\right)\bigg|_{r} = -\frac{q_t}{2\pi K r_e^2 h}\left(r_e^2 - r^2\right) \tag{A11}$$

Integrating on the both sides of Eq. (A11) from r to r_w:

$$\begin{aligned} \int_{r_w}^{r} d\psi' &= \frac{q_t}{2\pi K r_e^2 h}\int_{r_w}^{r}\left(r_e^2\frac{1}{r} - r\right)dr \\ \psi' - \psi'_{wf} &= \frac{q_t}{2\pi K h}\left[\ln\frac{r}{r_w} - \frac{1}{2}\left(\frac{r}{r_e}\right)^2\right] \end{aligned} \tag{A12}$$

The two-phase pseudo-pressure at formation average pressure can be defined as:

$$\psi'_R = \frac{\int_{r_w}^{r_e}\psi' dV}{\int_{r_w}^{r_e} dV} = \frac{2}{r_e^2}\int_{r_w}^{r_e}\psi' r dr \tag{A13}$$

Substituting Eq. (A12) into Eq. (A13), thus:

$$\psi'_R - \psi'_{wf} = \frac{2}{r_e^2}\frac{q_t}{2\pi K h}\int_{r_w}^{r_e}\left[\ln\frac{r}{r_w} - \frac{1}{2}\left(\frac{r}{r_e}\right)^2\right] r dr \tag{A14}$$

Through the integration on the right side of Eq. (A14), we can obtain:

$$\psi'_R - \psi'_{wf} = \frac{q_t}{2\pi K h}\left(\ln\frac{r_e}{r_w} - \frac{3}{4}\right) = \frac{q_t}{2\pi K h}\ln\frac{0.472 r_e}{r_w} \tag{A15}$$

When non-Darcy flow and the damage skin effects are considered, and the lab units of parameters in Eq. (A15) are converted into metric units, then:

$$\psi'_R - \psi'_{wf} = \frac{1.842 q_t}{Kh}\left(\ln\frac{0.472 r_e}{r_w} + S + D q_t\right) \tag{A16}$$

Appendix B. Calculation of two-phase pseudo-pressure

Based on Darcy's Law, the flow rate of each phase at standard condition can be given by:

$$q_w = 2\pi r h\frac{K K_{rw}}{B_w \mu_w}\frac{dp}{dr} \tag{B1}$$

$$q_g = 2\pi r h \frac{K K_{rg}}{B_g \mu_g} \frac{dp}{dr} \tag{B2}$$

Thus the water-gas ratio can be expressed by:

$$R_{wg} = \frac{q_w}{q_g} = \frac{K_{rw} B_g \mu_g}{K_{rg} B_w \mu_w} \tag{B3}$$

Equation (B3) can be transformed as:

$$\frac{K_{rw}}{K_{rg}} = R_{wg} \frac{B_w \mu_w}{B_g \mu_g} \tag{B4}$$

From Eq. (B4), it can be seen that for a given R_{wg}, the K_{rw}/K_{rg} value is depended on fluids' PVT data, and can be given at each pressure point in reservoir condition. The lab tested gas-water two-phase relative permeability curves give the correlation of K_{rw}, K_{rg}, and K_{rw}/K_{rg} vs. S_w. Therefore, through the application of implicit approach, at a given R_{wg}, the K_{rg}, K_{rw} and K_{rw}/K_{rg} can be correlated with pressure at reservoir condition. Then the pseudo-pressure ψ can be calculated in Eq. (B5) with trapezoid formula.

$$\begin{aligned} \psi &= \int_{p_0}^{p} \left(\rho_w \frac{K_{rw}}{\mu_w} + \rho_g \frac{K_{rg}}{\mu_g} \right) dp \\ &= \sum_{i=1}^{n} \frac{1}{2} \left[\left(\rho_w \frac{K_{rw}}{\mu_w} + \rho_g \frac{K_{rg}}{\mu_g} \right)_i + \left(\rho_w \frac{K_{rw}}{\mu_w} + \rho_g \frac{K_{rg}}{\mu_g} \right)_{i-1} \right] (p_i - p_{i-1}) \end{aligned} \tag{B5}$$

Nomenclature

B_g, B_w	gas and water formation volumetric factor, m^3/sm^3
D	non-Darcy flow coefficient, $(10^4 m^3/d)^{-1}$
h	reservoir thickness, m
K	reservoir permeability, mD
K_{rg}, K_{rw}	relative permeability of gas and water in a gas-water system
p_R	average reservoir pressure, MPa
p_{wf}	bottom hole flowing pressure, MPa
p_0	pressure at standard conditions,0.101MPa.
Q_{AOF}	is the gas Absolute Open Flow potential, $10^4 m^3/d$.
q_g	gas flow rate, $10^4 m^3/d$
q_w	water flow rate, m^3/d
q_t	total mass flow rate, kg/d
r_e	well drainage radius, m
r_w	wellbore radius, m
R_{wg}	water-gas flow rate ratio, m^3/m^3
S_a	apparent skin

S	skin caused by damage
T	reservoir temperature, K
z	gas deviation factor
$\bar{z}$	gas deviation factor at formation average pressure
Ψ_R, Ψ_{wf}	pseudo-pressure at average reservoir pressure p_R and bottom hole flowing pressure p_{wf}, $MPa^2/mPa{\cdot}s$
ψ'_R, ψ'_{wf}	gas-water two-phase pseudo-pressure at formation average pressure p_R and well bottom-hole flowing pressure p_{wf},$MPa.kg/m^3/mPa.s$
ρ_{gsc}, ρ_{wsc}	gas and water density at standard condition, kg/m^3
μ_g, μ_w	viscosity for gas and water, mPa·s
$\bar{\mu}$	gas viscosity at formation average pressure, mPa·s