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RESEARCH PAPER

Experiment on gas-water two-phase seepage and inflow performance curves of gas wells in carbonate reservoirs: A case study of Longwangmiao Formation and Dengying Formation in Gaoshiti-Moxi block, Sichuan Basin, SW China

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Abstract: Gas-water relative permeability was tested in the full diameter cores of three types of reservoirs (matrix pore, fracture and solution pore) in Gaoshiti-Moxi block under high pressure and temperature to analyze features of their gas-water relative permeability curves and gas well inflow dynamics. The standard plates of gas-water two-phase relative permeability curves of these types reservoirs were formed after normalization of experimental data. Based on the seepage characteristics of fractured reservoirs, the calibration methods of gas-water two-phase relative permeability curves were proposed and the corresponding plates were corrected. The gas-water two-phase IPR (inflow performance relationship) curves in different type reservoirs were calculated using the standard plates and validated by the actual performances of gas wells respectively. The results show that: water saturations at gas-water relative permeability equal points of studied reservoirs are over 70%, indicating strong hydrophilic; the dissolved cave type has the biggest gas-water infiltration interval and efficiency of water displacement by gas, followed by the matrix pore type and then fractured type; and the fractured type has the highest the permeability recovery degree, followed by the dissolved cave type and then matrix pore type. The calibrated gas-water two-phase relative permeability curves of fractured carbonate reservoirs can better reflect the gas-water two-phase seepage law of actual gas reservoirs and the standard plates can be used in the engineering calculation of various gas reservoirs. The characteristics of calculated IPR curves are consistent with the performance of actual producing wells, and are adaptable to guide production proration and performance analysis of gas wells.

Key words: carbonate reservoir; simultaneous production of gas and water; gas-water relative permeability curves; IPR curve; gas well

Introduction

In general, carbonate reservoirs have a large number of pores, vugs and fractures, and strong heterogeneity[1,2]. Besides, they also have bottom and edge water commonly, and thus wells in this kind of reservoir are likely to see water breakthrough and even watering-out[3]. Therefore, it is helpful for the efficient development of this kind of gas reservoir to study the gas-water two-phase seepage law, predict gas well production capacity and analyze gas production dynamics in carbonate reservoirs[4-5].

There are two kinds of methods to obtain the gas-water two-phase relative permeability curve. One is the direct measurement method, including the steady state method and the unsteady method[6]. The other is the indirect calculation method, including the capillary pressure curve, field data and empirical equation methods[7]. In steady-state methods, Diomampo et al. modeled the relative seepage law of water and gas in different shapes of fractures with the glass plate model[8–10], and Chinese researchers studied the multiphase seepage characteristics and the effects of high temperature and pressure on multiphase seepage in porous media[11–12]. In unsteady state methods, Jiang et al. measured the relative permeability with small core, confirming that the relative permeability curve obtained from fixed water saturation method could better represent multiphase seepage in the fracture-pore

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dual medium[13]. Zheng et al. studied the single-phase gas and gas-water two-phase seepage law under normal temperature and pressure and high temperature and pressure by using full diameter matrix core, man-made fracture-pore type core and fracture-vug type core[14]. In the research on productivity of gas-water wells, Sheng et al. derived the predicting model of gas-water production ratio by combining the binomial productivity equation with the law of gas-water two-phase flow and considering the turbulence effect[15]. Based on the steady-state seepage theory, Liu et al. established the steady-state seepage theory model of fractured gas reservoir with the equivalent seepage resistance method, derived the calculation formula of gas well production increment amplitude considering natural fractures, and analyzed the effects of natural fracture seepage parameters on gas well productivity[16]. So far most of the studies on gas-water two-phase seepage characteristics and two-phase gas well productivity in carbonate reservoirs focus on experiments or theoretical derivations, but there are few comprehensive studies on relative permeability and gas well productivity of multi-types of reservoirs.

The major gas pays in Gaoshiti-Moxi region are the Cambrian Longwangmiao and Sinian Dengying Formations, including a variety of reservoir types such as matrix pore type, fracture type and dissolution pore type. With active edge and bottom water in local areas, the reservoir is a typical fractured-vuggy carbonate gas reservoir in China. The geological conditions of the block meet the requirements of testing the gas-water two-phase relative permeability curve and seepage law. Moreover, abundant production data available make it easy to verify the dynamic characteristics of IPR in gas wells under the two-phase flow condition. Therefore, full diameter cores of matrix pore, fracture and dissolution pore-vug reservoir types in Gaoshiti-Moxi block were selected to testgas-water relative permeability under high pressure and temperature conditions, analyze characteristics of their gas-water relative permeability curves and corresponding gas well inflow dynamics.

1. Gas reservoir characteristics

1.1. Gas reservoir overview

In the Gaoshiti-Moxi block located in the middle of the Sichuan Basin, the Longwangmiao Formation reservoir is beach dolomite with the edge and bottom water in local parts, in which the reservoir space is mainly fractured-pore (vug) type, followed by pore type, with good configuration of pores, vugs and fractures. In contrast, the Dengying Formation reservoir is shoal-mound complex without edge and bottom water, including fractured-pore (vug) and pore (vug) two types.

The gas reservoir has a temperature of 420 K, an original water saturation of about 20%, and original pressures of 70 MPa. The overburden formation pressure is 110 MPa, the relative density of natural gas is 0.6, and the formation water is sodium chloride type.

1.2. Characteristics of different types of carbonate reservoirs

According to the development degree of pores, vugs and fractures, the carbonate reservoirs can be divided into three types, matrix pore type, fracture type and dissolution pore-vug type[17]. Cores of matrix pore type have rich micro-pores, no dissolution pores and vugs, and filled fractures or no fracture. Fracture reservoir cores have obvious open or partially filled fractures, and a small amount of dissolution pores and vugs in the matrix. In contrast, cores of dissolution pore-vug type reservoir have large numbers of dissolution pores and vugs, and micro-fractures between the pores and vugs. Statistics on porosity and permeability of nearly 200 full diameter cores from the Dengying and Longwangmiao Formations (Fig. 1) show that the matrix pore type reservoir has lowest porosity and permeability among the three types, the fracture type reservoir has higher permeability, but porosity, limited by matrix, of less than 10% in general. The dissolution pore-vug type reservoir has higher porosity and permeability, and physical properties much better than the other two types.

Table 1 shows the statistical results of characteristic parameters of different types of carbonate reservoirs, including overburden core porosity and permeability test, CT scan, nuclear magnetic resonance, high pressure mercury injection, stress sensitivity and flow regime experiment and so on.

The data shows that the static and dynamic parameters characterizing the physical and flow characteristics of the three types reservoirs differ widely. The matrix pore reservoir has low porosity, permeability and surface porosity, higher proportion of small pores, and only a small amount of large pores, no dissolution vugs, low movable fluid saturation, high threshold and median pressure, strong stress sensitivity, and weak high-speed non-Darcy effect. The fracture type reservoir has higher porosity, permeability and surface porosity, higher proportion of medium, small and microscopic pores, some large pores and dissolution vugs, higher movable fluid saturation, lower threshold and median pressure, strong stress sensitivity, and stronger high speed non-Darcy effect. The dissolution pore-vug type reservoir has high porosity, permeability

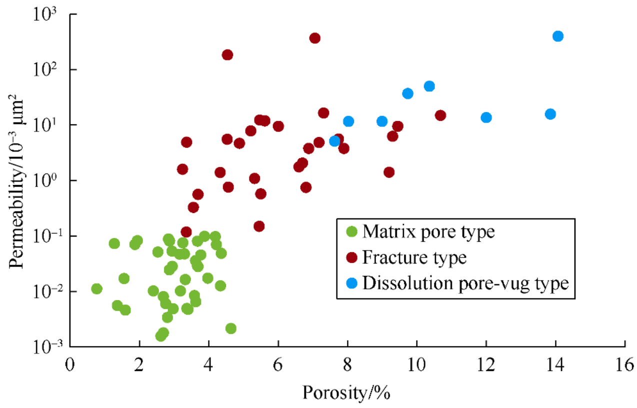

Fig. 1. Porosity and permeability of full diameter cores from Dengying and Longwangmiao Formations.

Table 1. Characteristic parameters of different types of carbonate reservoirs.

Reservoir type	Permeability/10^{-3} μm^2	Porosity/%	Surface porosity/%	Proportion of different sizes of pores/%			Movable fluid saturation/%	Threshold pressure/MPa	Median pressure/MPa	Stress-sensitive power exponent	Forchheimer number
				Medium, small, micro pores	Large pores	Vugs					
Matrix pore type	0.000 1-0.1	0-3	0-2	67-95	5-33	0	10-40	0.5-20	10-300	0.6	0-0.03
Fracture type	0.1-50	2-15	2-10	52-90	10-43	0-5	30-80	0.001-0.3	3-30	0.6	0.03-1
Dissolution pore-vug type	1-100	6-20	6-20	10-31	52-80	17-30	60-95	0.001-0.3	0.1-5	0.1	0.2-3

Note: The pore levels divided by transverse relaxation time of magnetic resonance are micro-pore of 0–1 ms, small pore of 1–10 ms, medium pore of 10–100 ms, large pore of 100–1 000 ms, and dissolution vug of more than 1 000 ms.

Table 2. Calculated displacement pressures of gas-water relative permeability experiment of different carbonate reservoirs.

Reservoir type	Core number	Length/cm	Diameter/cm	Permeability/10^{-3} μm^2	Porosity/%	Displacement pressure/MPa	Notes
Matrix pore type	MPT No. 1	10.604	6.678	0.029 5	2.20	3.82	
	MPT No. 2	10.112	6.550	0.043 9	1.90	2.91	
	MPT No. 3	10.306	6.538	0.021 1	2.30	4.62	
Fracture type	FT No. 1	8.258	6.698	0.600 0	2.70	0.93	After fracturing
				0.002 6	1.50	10.63	Before fracturing
	FT No. 2	7.956	6.532	5.200 0	3.30	0.35	After fracturing
				0.007 9	2.10	7.22	Before fracturing
Dissolution pore-vug type	DCT No. 1	10.350	10.159	13.700 0	12.00	0.41	
	DCT No. 2	10.250	10.156	37.200 0	9.74	0.23	

and surface porosity, low proportion of medium, small and microscopic pores, much higher proportion of large pores and dissolution vugs, high movable fluid saturation, low threshold and median pressure, weak stress sensitivity, and strong high speed non-Darcy effect.

2. Design of gas-water relative permeability experiment

2.1. Experiment samples

Full diameter cores used in the experiment are from Gaoshiti-Moxi block. Among them, cores of dissolution pore-vug type are taken from the Longwangmiao Formation, and the other cores are from Deng 4th member of Dengying Formation, and both the formations are major reservoirs.

2.2. Experiment parameters

According to the basic characteristics of the gas reservoir and laboratory conditions, the experiments were set at the temperature of 323 K, overburden pressure of 50 MPa, formation water viscosity and salinity of 1.093 mPa·s and 80 000 mg/L respectively, the water type was sodium chloride, and the nitrogen viscosity was 0.017 6 mPa·s. In the experiment, the whole digital hydraulic servo rock mechanics experiment system was used to create fractures, and the core displacement pressure adopted the standard SY/T5345-2007[6]. According to the core properties, the formula of initial pressure difference is as follows:

$$\pi_1 = \frac{\sigma \times 10^{-3}}{\sqrt{K / \phi \times 10^{-3}}\,\Delta p} \le 0.6 \tag{1}$$

The displacement pressure was calculated by assuming π_1 as 0.5 and the interface tension between nitrogen and water as 70 mN/m (Table 2).

2.3. Experiment methods and processes

Gas-water two-phase seepage experiment can be done in two forms, water driving gas and gas driving water. As there is no gas flow display in the experiment of water driving gas after water breaks through at the outlet, this way of experiment is difficult to obtain experiment data and has less data points, and the result is mainly seepage curve of single water phase. Therefore, about 90% of the current seepage experiments are conducted in gas driving water form, and the gas-water relative permeability curves in gas reservoir engineering are obtained by this method in most cases. Regardless of water driving gas or gas driving water, the irreducible water saturation is basically the same and the range of joint water-gas seepage interval is basically consistent. Therefore, the non-steady gas driving water mode was chosen to measure gas-water two-phase relative permeability of full diameter cores of carbonate rocks.

The experimental apparatus is shown in Fig. 2 and the specific steps are as follows. (1) The rock samples were polished, pretreated, dried at 60 °C for 24 hours and weighed. (2) After vacuumized for 24 hours, the sample was saturated with for-

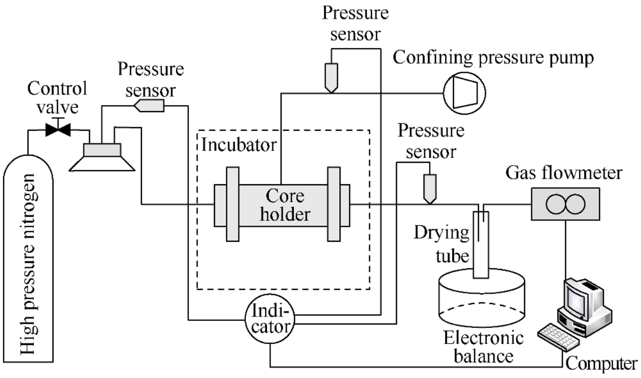

Fig. 2. Schematic diagram of apparatus used to measure gas-water relative permeability in unsteady form.

mation water for 24 hours under the pressure of 10 MPa. (3) Then the appropriate displacement pressure was selected according to the water permeability data. (4) Finally the saturated core was put into the core holder horizontally, and the gas was injected at the selected displacement pressure to drive water until water didn't come out of the outlet any more.

3. Analysis and processing of experimental results

3.1. Experimental data and normalization

Following the "testing method of two phase relative permeability in rocks" in the standard SY/T5345-2007, the experimental data of gas-water two-phase seepage law of full diameter cores were processed to obtain the gas-water relative permeability curves of different types of reservoirs, including matrix pore type, fracture type and dissolution pore-vug type (Fig. 3). And the experimental data was normalized to obtain the normalized relative permeability curves shown in Fig. 4.

3.2. Comparison of gas - water relative permeability characteristics of different types of cores

According to the experimental data, the characteristic parameters of gas-water relative permeability curve were counted (Table 3). The degree of permeability recovery in Table 3 is the ratio of gas phase permeability at irreducible water saturation to that at zero water saturation. The results show that the carbonate cores are obviously hydrophilic, with the minimum water saturation of 72.88% and maximum water saturation of 93.23% at the isotonic permeability point. Moreover, cores of the same type have similar characteristic parameters like irreducible water saturation, water saturation range of two-phase co-seepage, gas displacing water efficiency and permeability recovery degree, but cores of different types have different distribution ranges. These indicate that cores of the same type have similar experiment results, while cores of different types are very different in characteristics of gas-water relative permeability curves.

3.3. Standard plates of gas-water relative permeability curves of carbonate reservoirs

The gas-water two-phase relative permeability curves of the same type of reservoir cores were averaged and inversely calculated after normalization to form a standard plate of gas-water relative permeability curve of this type of core (Fig. 5) so as to facilitate the calculation of various types in gas reservoir engineering. Statistics on characteristic parameters

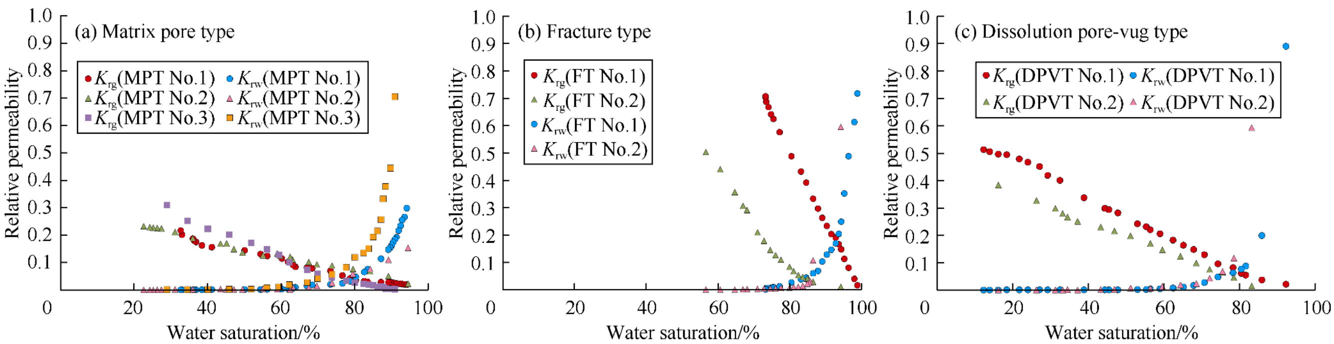

Fig. 3. Gas-water relative permeability curves of carbonate cores.

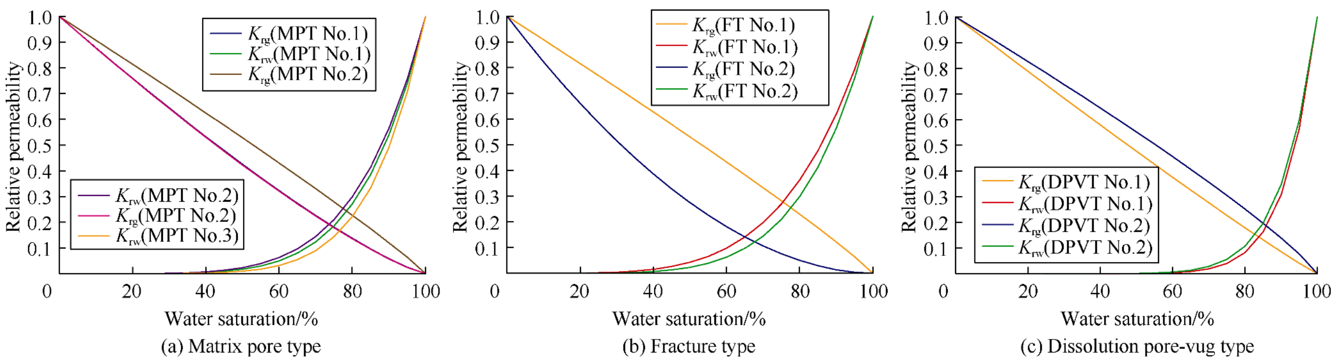

Fig. 4. Normalized curves of gas-water relative permeability of carbonate cores.

Table 3. Statistics on relative permeability characteristics of gas-water two-phase seepage experiment of carbonate cores.

Reservoir type	Core No.	Irreducible water saturation/%	Gas-water two-phase common seepage interval range/%	Gas flooding efficiency/%	Degree of permeability recovery/%	Water saturation at isotonic point/%
Matrix pore type	MPT No. 1	32.71	32.71–94.20	65.20	21.59	79.18
	MPT No. 2	22.60	22.60–94.55	76.21	23.20	81.25
	MPT No. 3	28.95	28.95–90.94	68.19	30.09	73.76
Fracture type	FT No. 1	73.26	73.26–98.91	26.00	70.60	93.23
	FT No. 2	56.62	56.62–94.26	39.77	50.37	85.40
Dissolution pore-vug type	DCT No. 1	12.34	12.34–92.37	86.59	51.29	79.02
	DCT No. 2	16.15	16.15–83.26	80.54	38.38	72.88

of the standard plates (Table 4) show: (1) The carbonate reservoirs of the Longwangmiao and Dengying Formations in Gaoshiti-Moxi block are strongly hydrophilic, with the water saturations at isotonic point between 73.86% and 87.03%, in which the fracture type has the highest water saturation at isotonic point. (2) The fracture type reservoir has the narrowest water saturation range of gas-water co-seepage and the highest irreducible water saturation; the dissolution pore-vug type has the largest water saturation range of gas-water co-seepage and lowest irreducible water saturation; while the matrix pore type is between the above two. The main reason is that the heterogeneity degree of dissolution pores, vugs and fractures in cores determines the level of irreducible water saturation. The fracture type core has the strongest heterogeneity, so the gas displaces water in the fractures largely, and hardly any water in the matrix pores, which leads to the highest irreducible water saturation of this type. The dissolution pore-vug type core has good connectivity of dissolution pores and vugs, weak heterogeneity, good gas displacing water effect, and thus low irreducible water saturation. (3) Different types of reservoirs differ widely in the recovery degree of gas phase relative permeability at irreducible water saturation after gas driving, and the fractured type has the highest while the matrix pore type the lowest. The main reason is that the main seepage channels of fractured cores are fractures, although the gas driving efficiency is the lowest, the water in the fractures is almost completely driven out, thus the permeability recovery is the highest. The dissolution pore-vug type has good physical properties and the highest gas driving efficiency, so most of the mobile water is driven out, and the gas permeability recovery is also relatively high. By contrast, with tiny pore throats, the matrix pore type has higher irreducible water saturation in itself, and the gas permeability recovery is the lowest. (4) Compared with the characteristics of gas-water relative permeability curves of sandstone, the matrix pore type carbonate is similar to that of homogeneous tight sandstone, and the dissolution pore-vug type carbonate is similar to that of medium and high permeability homogeneous sandstone.

3.4. Correction of gas-water relative permeability curves of fractured type cores

In the standard plate of fracture type, when the overall water saturation of the fractured reservoir is less than 65%, only gas flows in the reservoir; the water phase starts to flow only

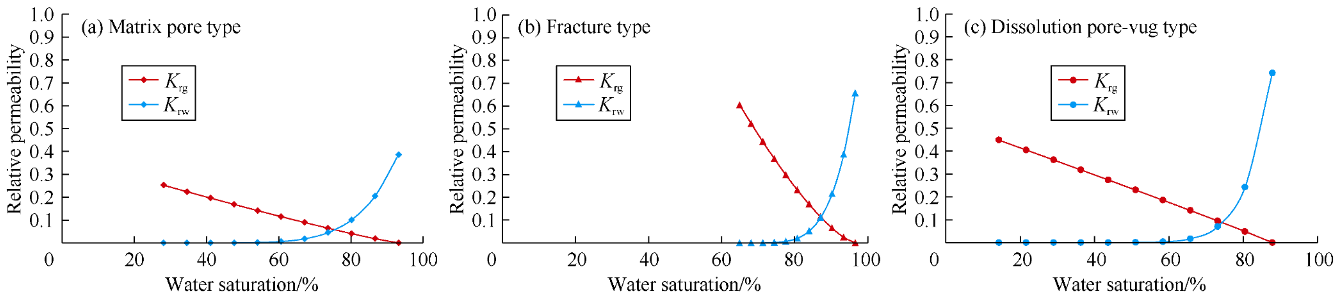

Fig. 5. Standard plates of gas-water relative permeability of carbonate reservoirs.

Table 4. Statistics on characteristic parameters of standard gas-water two-phase seepage curves of carbonate cores.

Reservoir type	Irreducible water saturation/%	Gas-water two-phase common seepage interval range/%	Gas flooding efficiency/%	Degree of permeability recovery/%	Water saturation at isotonic point/%
Matrix pore type	28.09	28.09–93.23	69.80	25.23	76.21
Fracture type	65.00	65.00–96.60	32.98	60.50	87.03
Dissolution pore-vug type	14.25	14.25–87.81	83.81	44.84	73.86

when the water saturation is more than 65%. However, when water coning occurs in gas reservoirs with edge or bottom water, water will invade along fractures in fractured reservoirs even though the overall water saturation is low, resulting in water production and even serious watering-out. Clearly, the gas-water relative permeability curve of fractured carbonate cores above can't reflect the law of gas-water two-phase seepage in the actual production. The reason is that the processing method of conventional core gas-water seepage experimental data is based on the B-L theory[6], which is only applicable to gas-water seepage analysis of homogeneous or apparently homogeneous reservoirs. Fractured carbonate reservoirs have strong heterogeneity, and fracture permeability much larger than that of bedrock permeability with difference of about 100 times or higher. During the process of gas driving water, the velocities of the fluids in fractures and matrix differ greatly, and the conventional processing method cannot reflect this characteristic.

According to the literature[18,19], the gas-water static contact angle θ_{wg} of bedrock is generally lower than 40°, and the capillary pressure can be expressed as:

$$p_c = \frac{2\times10^{-3}\sigma\cos\theta_{wg}}{r} \tag{2}$$

Based on the capillary flow model, the pore throat radius of the bedrock satisfies the following relation:

$$r = \sqrt{\frac{8\times10^{-9}K_m}{\phi_m}} \tag{3}$$

By substituting formula (3) into formula (2), we can obtain,

$$p_c = \frac{10^{-3}\sigma\cos\theta_{wg}}{\sqrt{\frac{2\times10^{-9}K_m}{\phi_m}}} \tag{4}$$

The σ value is 70 mN/m, and the θ_{wg} value is 40°. The capillary pressures of two fracture type cores in Table 2 before fractured calculated by using formula (4) are 2.88 MPa and 1.959 MPa, respectively. The pressure differences of them after fractured from gas driving experiment are 0.93 MPa and 0.35 MPa, respectively, much lower than the capillary pressure of the bedrock. Therefore, in the gas driving water experiment of fractured carbonate cores, only water in the fractures is driven out, and the experimental results just reflect the law of the gas-water flow in fractures.

Therefore, the gas-water relative permeability curves of fractured carbonate reservoirs need to be corrected. The following assumptions are made in gas driving water of fractured rocks: (1) The bedrock permeability is much lower than the fracture permeability. (2) The gas driving water process only drives out the water in the fractures and the water saturation in the bedrock is always the original water saturation. That is to say, the water saturation in the relative permeability curve is the water saturation in fractures. (3) The water saturation in fractures is the irreducible water saturation of the fracture at the end of the gas driving.

Based on the material balance equation, the porosity of fractured carbonate cores satisfies the following relationship,

$$\phi = \phi_m + \phi_f \tag{5}$$

The water saturation of fractured carbonate core satisfies the following relationship,

$$S_w\phi = S_{wm}\phi_m + S_{wf}\phi_f \tag{6}$$

According to the formula (6), the calculation formula of fracture water saturation can be written as:

$$S_{wf} = \frac{S_w\phi - S_{wm}\phi_m}{\phi_f} \tag{7}$$

Formula (7) is the relationship between the water saturation in fractures and the overall carbonate core.

When the water saturation in fractures is equal to 0,

$$K_{rg}\left(S_{wf}=0\right)=1 \tag{8}$$

The normalized gas-water relative permeability curve of the fractured-type carbonate core is extended until K_{rg} is equal 1, and the corresponding core water saturation is named as S_{wl} (Fig. 6). From the result, the S_{wl} value is 58.07%, combined with formula (7), we can obtain:

$$S_{wl}\phi - S_{wm}\phi_m = 0 \tag{9}$$

According to the formula (9), the bedrock porosity can be written as:

$$\phi_m = \frac{S_{wl}}{S_{wm}}\phi \tag{10}$$

By substituting formula (10) and formula (5) into formula (7), the water saturation in fractures during gas driving water process can be written as,

$$S_{wf} = \frac{S_w - S_{wl}}{1-\frac{S_{wl}}{S_{wm}}} \tag{11}$$

The relative permeability curves of fractured carbonate rocks shall be corrected by the formula (11) to obtain the relative permeability curves of gas -water two-phase flow in fractures (Fig. 7). According to the results, the irreducible water saturation of the fractures is 16.72%, and the actual water saturation range of gas-water two-phase flow is between 16.72% and 91.81%, the efficiency of gas driving water is 81.79%, while the water saturation range of water-gas two

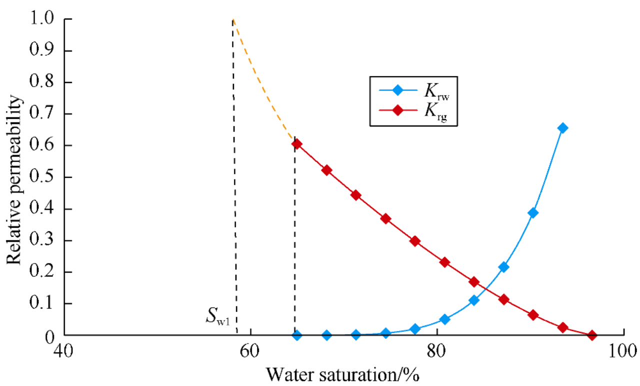

Fig. 6. Extension curve of gas phase relative permeability of fractured carbonate core.

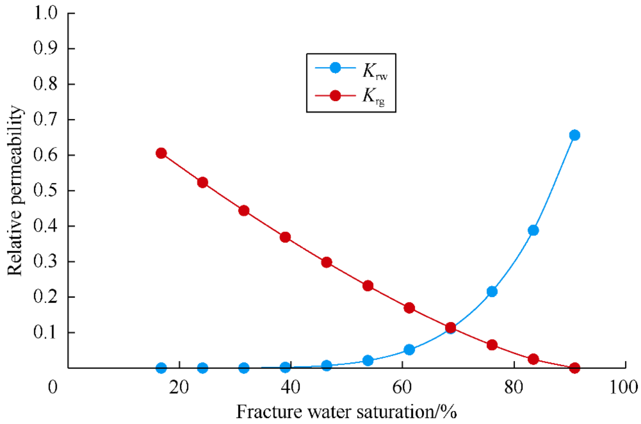

Fig. 7. Standard plate of gas-water relative permeability curve of fractured reservoir.

phase flow of the whole core is between 65.00% and 96.60%, and the gas driving water efficiency is 32.99%. It can be seen the gas driving water efficiency in the fractures is 2.48 times that of the whole core, which is closer to the actual situation of gas well production. The corrected gas-water relative permeability curve of fractured carbonate reservoir can better reflect the law of gas-water two-phase seepage in actual gas reservoir, and can be applied in various calculation of gas reservoir engineering.

4. Calculation of IPR curve and example analysis

4.1. IPR equation of gas production with water

Based on the existing research results[17], considering the stress sensitivity of the reservoir and the effect of gas non-Darcy seepage, the gas deliverability equation of gas-water producing fracture-vug type carbonate reservoir can be expressed as:

$$\psi_{\mathrm{R}} - \psi_{\mathrm{wf}} = Aq_{\mathrm{t}} + Bq_{\mathrm{t}}^2 \tag{12}$$

where,

$$A = \frac{1.842\times10^{-3}}{KK_{\mathrm{rg}}h}\ln\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}} \qquad K = K_{\mathrm{i}}\left(\frac{\sigma_{\mathrm{s}}-p}{\sigma_{\mathrm{s}}-p_{\mathrm{i}}}\right)^{-\alpha}$$

$$B = \frac{4.036\times10^{-21}\beta\rho_{\mathrm{g}}}{r_{\mathrm{w}}^2h^2\mu_{\mathrm{g}}} \qquad \beta = \frac{7.0\times10^9}{K_{\mathrm{i}}^{1.42}}$$

$$\psi = \int_0^p\left(\frac{\rho_{\mathrm{g}}K_{\mathrm{rg}}}{\mu_{\mathrm{g}}} + \frac{\rho_{\mathrm{w}}K_{\mathrm{rw}}}{\mu_{\mathrm{w}}}\right)\mathrm{d}p \tag{13}$$

$$q_{\mathrm{t}} = q_{\mathrm{sc}}\rho_{\mathrm{gsc}} + q_{\mathrm{w}}\rho_{\mathrm{wsc}} \tag{14}$$

$$q_{\mathrm{w}} = \frac{KK_{\mathrm{rw}}h}{1.842\times10^{-3}B_{\mathrm{w}}\mu_{\mathrm{w}}\ln\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}}\left(p_{\mathrm{R}} - p_{\mathrm{wf}}\right) \tag{15}$$

Combining the above equation with the seepage curve from experiment, the gas and water production IPR curve can be calculated and the performance analyzed.

4.2. Calculation of IPR curve

The carbonate reservoirs of Gaoshiti-Moxi block are 4700 m in burial depth and 30 m in effective thickness. Under the original conditions, the permeabilities of matrix pore type, fracture type and dissolution pore-vug type carbonate reservoirs are 0.07×10^{-3} μm^2, 4×10^{-3} μm^2, and 10×10^{-3} μm^2, respectively. The gas well has a wellbore diameter of 0.1 m, and discharge radius of 1000 m. With edge and bottom water, the gas reservoir will see rise of water saturation due to later water invasion, thus the standard gas-water relative permeability curve is used in the calculation.

For fractured carbonate reservoirs, the initial water saturation in bedrock is consistent with that in fractures, and they are the total irreducible water saturation of the reservoir. The permeability of the bedrock is much lower than that of the fractures, and water invasion only occurs in fractures. The water saturation in fractures increases sharply while that in matrix changes little during water invasion. According to formula (6), the whole water saturation of the reservoir can be expressed as:

$$S_{\mathrm{w}} = S_{\mathrm{wc}} + \left(S_{\mathrm{wf}} - S_{\mathrm{wc}}\right)\frac{\phi_{\mathrm{f}}}{\phi} \tag{16}$$

According to the data of gas-water relative permeability curve of fractured type reservoir, the whole water saturation of the fractured reservoir is calculated inversely by using the formula (16). And the IPR curve of the fractured reservoir can be obtained at different water saturation conditions.

By using the formulas (12) to (16), the gas and water IPR curves of three types of carbonate gas reservoirs in different water saturation conditions are calculated (Figs. 8 and 9). From the results we can see that the water saturation has a great effect on gas production capacity of three types of reservoirs. Even when it is close to the irreducible water saturation (20%), the absolute open flow (AOF) with water is far less than that without water. The fracture type reservoir is the least affected by water saturation, with the AOF near irreducible water saturation being about 59.90% of that without water. The reason is that the main seepage channel of this type of reservoir is fractures, even in the condition without water, and the production capacity of the matrix is limited, and the production capacity of the matrix has little impact on the whole production capacity after water breakthrough. The matrix pore reservoir is affected most strongly by water saturation, with AOF near irreducible water saturation being about 27.97% of that without water, because the pore throats of this type reservoir are small and poorly connected, once breaking through, the water will block most seepage channels. The dissolution pore-vug type reservoir is between the two, with the AOF near irreducible water saturation being about 55.00% of that without water. This is mainly because the reservoir space of this type is relatively homogeneous and the seepage capacity is stronger than that of the matrix pore reservoir, and the water breakthrough will have an effect on the whole reservoir. Moreover, with the increase of water saturation, the effect of water saturation on the production capacity weakens gradually after water breakthrough, and the reason is that the water early has blocked most seepage channels.

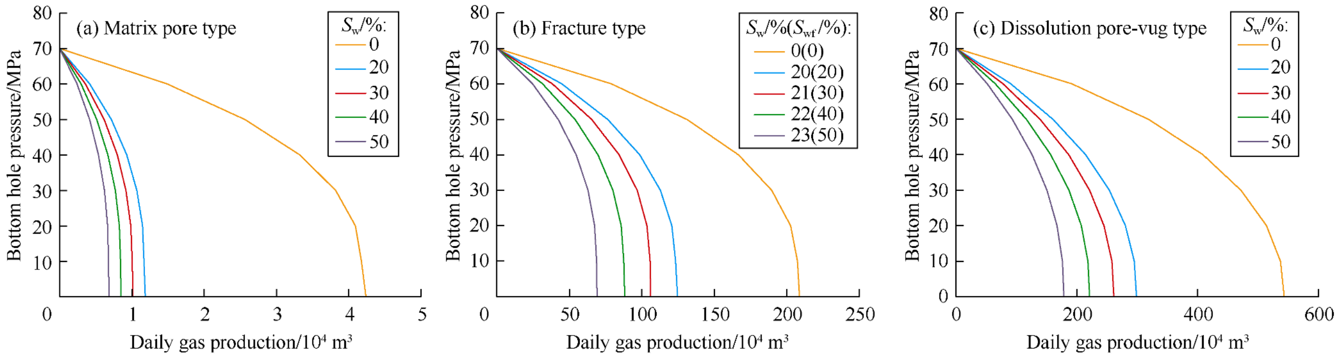

Fig. 8. Gas-phase IPR curves of different types of gas reservoirs under different water saturation conditions.

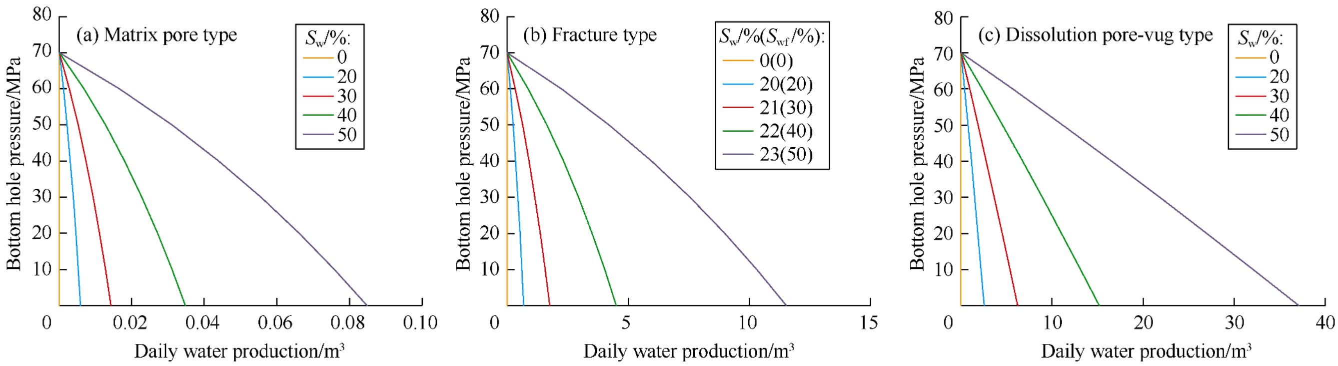

Fig. 9. Water-phase IPR curves of different types of gas reservoirs under different water saturation conditions.

The IPR curve of water phase has regularity contrary to that of the gas phase. Although water saturation has a great impact on gas production in the early water breakthrough, the water production capacity is smaller. With the increase of water saturation, the water production capacity increases rapidly. The higher the water saturation, the faster the water production capacity increases, and this is why gas wells will be flooded rapidly after water breakthrough.

4.3. Analysis of production wells

Well Gao 1, Gao 2 and Gao 3 are three production wells in Gaoshiti-Moxi block. According to logging results, the main gas pays of them are fracture type, dissolution pore-vug type and matrix pore type, respectively. Among them, the reservoir of Well Gao 3 has weak seepage ability, and low gas and water production capacity. The well did not have the value of industrial development, and the reservoir hardly produced gas before fracturing.

The production performance curve of Well Gao 1 is shown in Fig. 10. The well had low water production and higher gas productivity initially. Ten months into production, its water production started to increase from 15 m^3/d to 40 m^3/d, while the gas production decreased from 60×10^4 m^3 to 30×10^4 m^3. According to the IPR curve, as the water saturation of fractured reservoirs increases by 3% from near irreducible water saturation (20%), the capacity of gas production would decrease by 44.54%, and the water production capacity would increase by 16 times, and the actual production performance of Well Gao 1 is in accord with this law.

The production performance curve of Well Gao 2 is shown in Fig. 11. During the nearly 20 months of its production, it had low and stable water production. It can be certain that the water produced is a small amount of bound water or condensate water carried by the gas flow. Its gas production is basically stable and high. The dissolution pore-vug reservoir

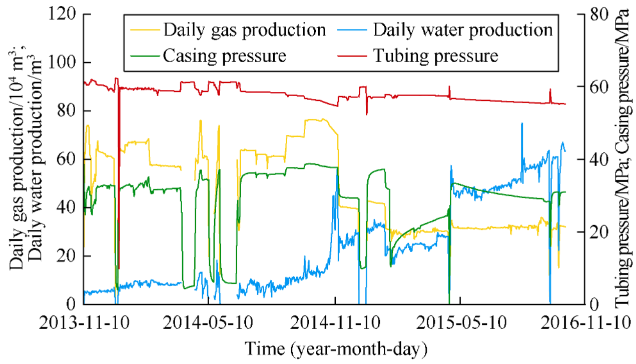

Fig. 10. Production performance curve of Well Gao 1.

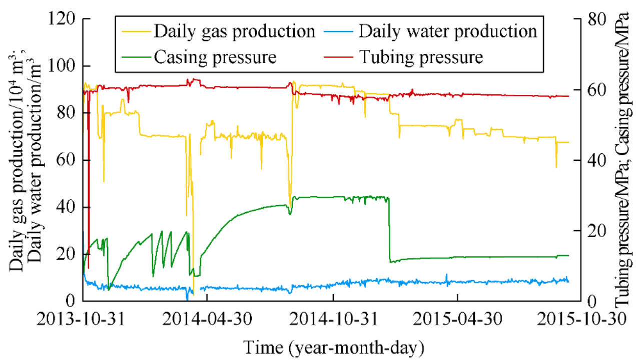

Fig. 11. Production performance curve of Well Gao 2.

is relatively homogeneous, without relative high seepage channel, so water coning advances slowly, and water and gas production are relatively stable and can maintain for a long time. The production performance of Well Gao 2 is consistent with the characteristics of IPR curve of dissolution pore-vug reservoir.

In summary, the gas-water two-phase seepage law plays a decisive role in the production of the three types of reservoirs. The productivity of gas wells in fractured reservoirs is high, but greatly affected by the change of water saturation. It is suggested that there should be enough distance between the perforated section of the production well and gas-water interface to avoid the advance of early water breakthrough. At the same time the drawdown pressure should be controlled to delay the speed of water invasion and extend the gas recovery period without water. The gas wells in dissolution pore-vug reservoir have high gas production capacity and slow waterline advancing rate, so their productivity can be higher, but not much, to prevent the waterline from pushing fast and avoid watering-out. If a well has multiple types of reservoirs, research on commingle production should be done.

5. Conclusions

The experimental study shows that the carbonate cores have water saturations of equal gas and water permeability of over 70%, and strong hydrophile. In terms of the gas-water co-seepage range of water saturation and gas-driving water efficiency, the dissolution pore-vug type ranks the first, the fracture type ranks the last, and the matrix pore type is in between the above two. In terms of permeability recovery degree, the fracture type is the highest, the matrix pore type is the lowest, and the dissolution pore-vug type is in between.

The corrected gas-water two-phase relative permeability curves of fracture type carbonate reservoir can better reflect the gas-water two-phase seepage law of the gas reservoir.

The standard plates of gas-water two-phase relative permeability curves of different types of carbonate reservoirs obtained from normalization and correction of experimental data can be used in the engineering calculations of various gas reservoirs. The IPR curves calculated on this basis are consistent with the performance of producing wells, so they can be used to guide production proration and performance analysis of gas wells.

Nomenclature

B_w—Volume factor of formation water, f;

h—Reservoir effective thickness, m;

K—Permeability, 10^{-3} μm^2;

K_i—Original reservoir permeability, 10^{-3} μm^2;

K_m—Matrix permeability, 10^{-3} μm^2;

K_{rg}—Relative permeability of gas phase, dimensionless;

K_{rw}—Relative permeability of water phase, dimensionless;

p—Pressure, MPa;

p_c—Capillary pressure, Pa;

p_i—Original reservoir pressure, MPa;

p_R—Pressure at external boundary, MPa;

p_{wf}—Bottom hole pressure, MPa;

Δp—Displacement pressure difference, MPa;

q_{sc}—Gas production rate under standard condition, m^3/d;

q_t—Total gas and water production of gas well, kg/d;

q_w—Water production, m^3/d;

r—radius of pore throat, mm;

r_e—Drainage radius, m;

r_w—Gas well radius, m;

S_w—Water saturation of whole fractured core, %;

S_{wc}—Irreducible water saturation, %;

S_{w1}—Overall water saturation of the core when the gas phase relative permeability curve extends to K_{rg}=1, %;

S_{wf}—Water saturation in fractures, %;

S_{wm}—Water saturation in bedrock, %;

α—Stress- sensitive power exponent, the matrix pore type and the fracture type are both 0.6 and the dissolution pore-vug type reservoir is 0.1;

β—Coefficient of non-Darcy seepage, m^{-1};

θ_{wg}—Gas-water static contact angle, (°);

μ_g—Gas viscosity, mPa·s;

μ_w—Formation water viscosity, mPa·s;

π_1—Ratio of capillary pressure to displacement pressure, dimensionless;

ρ_g—Gas density, kg/m^3;

ρ_{gsc}—Gas density under standard condition, kg/m^3;

ρ_w—Formation water density, kg/m^3;

ρ_{wsc}—Formation water density under standard condition, kg/m^3;

σ—Interfacial tension, mN/m;

σ_s—Overburden pressure, MPa;

ϕ—Core porosity, %;

ϕ_f—Fracture porosity, %;

ϕ_m—Bedrock porosity, %;

ψ—Pseudo-pressure of gas-water two-phase, kg·MPa/(mPa·s·m^3);

ψ_R—Pseudo-pressure of gas-water two-phase of the gas reservoir outer boundary, kg·MPa/(mPa·s·m^3);

ψ_{wf}—Pseudo-pressure of gas-water two-phase at the bottom hole, kg·MPa/(mPa·s·m^3).

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