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Research Article

Reserve Estimation from Early Time Production Data in Geopressured Gas Reservoir: Gas Production of Cumulative Unit Pressure Drop Method

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There is high uncertainty in reserve estimation during the early development of deep ultrahigh pressure gas reservoirs, largely because it remains challenging in accurately determining the formation compressibility. To overcome this, starting from the definition of compressibility, a novel gas production of cumulative unit pressure drop analysis method was established, of which the effectiveness was proven by applications in calculating the reserves of three gas reservoirs. It has been found that, in the limiting case, i.e., when the formation pressure dropped to the normal atmospheric pressure, the dimensionless gas production of the cumulative unit pressure drop was the reciprocal of the initial formation pressure. Besides, the relationship curve of the dimensionless gas production of the cumulative unit pressure drop and pressure drop was a straight line in the medium term, extending the straight line and intersecting the vertical line passing through the original formation pressure point, and the reserves can be determined according to the intersection point and the initial formation pressure. However, due to the influence of natural gas properties, the value needs further correction, and the correction coefficient depends on the pseudocritical temperature of natural gas. Specifically, when the pseudocritical temperature is given, the correction coefficient would be close to the minimum value of the natural gas deviation factor. When the pseudocritical temperature is more than 1.9 and less than 3.0, the minimum deviation factor would be between 0.90 and 1.0, and the higher the pseudocritical temperature, the closer the ratio is to 1.0.

1. Introduction

The proportion of natural gas in primary energy consumption has been continuously increasing since the beginning of the 21st century, demonstrating its importance as a global strategic resource and a livelihood material. According to existing reports [1], 61% of natural gas reserves which were discovered worldwide in the past decade are distributed in deep zones and are characterized by strong ground stress, high heterogeneity, temperature, and pressure. High pressure gas reservoirs have downward curving $p/Z \sim G_p$ behavior. Precise estimation of the reserves of such gas reservoirs is crucial for reservoir engineers. However, reserve estimation's basic method is the material balance method [2]. The formation compressibility is one of the key parameters in the material balance equation of a high pressure gas reservoir but challenging to determine; the error in estimates could even exceed 100% [3]. For many years, the petroleum industry has relied on Hall's correlation [4] for estimating pore volume compressibility. This correlation was developed from

Table 1: Published studies of reserve estimate problem of high pressure gas reservoir.

No.	Ref.	Year	Author	Solution method			Need pore volume compressibility	Advantages and disadvantages
1	[3]	1971	Hammerlindl	Polyline analysis method	Hammerlindl method	Average formation compressibility	✓	Gradient > 1.13 MPa/100 m
2						Material balance	✓	
3	[7]	1983	Chen		Chen Yuanqian method		✓	Volumetric gas reservoirs, pressure coefficient at the transition point is 1.2~1.3
4	[8]	2001	Gan		Gan-Blasingame		X	No pore volume compressibility is required, and it can be calculated whether the curve inflection point appears or not
5	[9]	1981	Ramagost	Linear regression method	Ramagost-Farshad		✓	Volumetric gas reservoirs
6	[10]	1981	Roach		Roach		X	Pore volume compressibility can be calculated, but it is sensitive to the original pressure data
7	[11]	1994	Poston		Improved Roach method		X	It is suitable for water drive gas reservoirs and can calculate the reserves before water invasion, the size of water invasion, and the effective compressibility coefficient
8	[12]	1993	Becerra-Arteaga		Becerra-Arteaga		X	Need gradient
9	[2]	1963	Havlena		Havlena-Odeh		X	Suitable for water intrusion gas reservoirs, sensitive to original pressure and early data; if it is a closed gas reservoir, the rock compressibility coefficient can be calculated
10	[13]	1993	Yuanqian	Nonlinear regression method	Binary regression		X	Knowing the variation law of natural gas deviation coefficient; this method can calculate dynamic reserves and compressibility
11	[14]	2008	Gonzalez		Nonlinear regression method	Quadratic production model	X	Dimensionless linear coefficient is less than 0.4
12	[15]	2011	Qin			Trinomial approximation	X	The shape of the curve is not easy to control and may cause large errors
13	[16]	2017	Jiao			Limit form	X	Volumetric gas reservoirs
14	[17]	2019	Sun			Power function form	X	Volumetric gas reservoirs
15	[18]	1991	Ambastha	Type curve matching	Ambastha method		X	Volumetric gas reservoirs, original pressure, and temperature are known in type curve matching, strong multisolution
16	[19]	1998	Fetkovich		Fetkovich method		X	Considering the influence of nonreservoir dissolved gas, inversely calculate the compressibility and the size of the water body
17	[14]	2008	Gonzalez		Gonzalez method	Quadratic production model	X	Mainly used to verify the results of other methods
18	[6]	2020	Sun		Single log match analysis		X	Volumetric gas reservoirs

Table 1: Continued.

No.	Ref.	Year	Author	Solution method	Need pore volume compressibility	Advantages and disadvantages
19	[20]	2001	Marhaendrajana	Multiwell modern production decline analysis method	✓	Without considering the impact of water invasion, only reserves of connected well groups can be calculated
20	[21]	1998	Walsh	Trial analysis method	✓	It can be used to calculate the volume of water bodies and calculate the water-soluble gas reserves

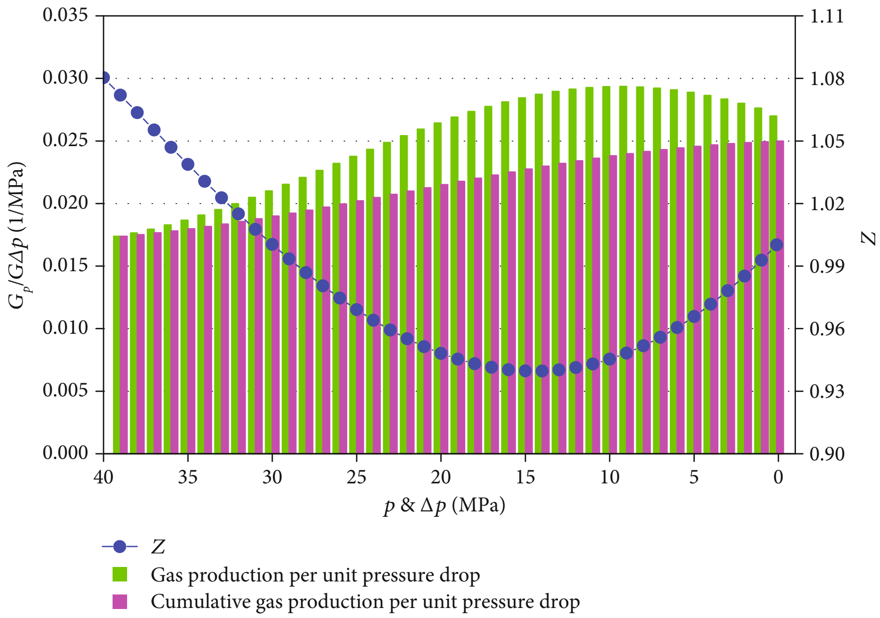


Figure 1: Gas production per unit pressure drop and dimensionless gas production of cumulative unit pressure drop (formation pressure is 40 MPa, formation temperature is 373.15 K, and gravity of gas is 0.6).

measurements on seven consolidated limestone and five consolidated sandstone samples. Compressibilities, however, are highly affected by reservoir type and overburden conditions.

According to the classical theory, the material balance $p/Z \sim G_p$ curve of a high pressure gas reservoir has a two-segment characteristic [5], with the second straight line segment occurring late (apparent formation pressure drops by 6%-38%). However, for high pressure and ultrahigh pressure gas reservoirs at the early stage of development, even if the production test time is up to 1 year and the drawdown scope reaches 3%-38% of the initial formation pressure or even higher, the starting point deviating from the early straight line segment would still not occur, and thus, the starting condition of using the material balance method to calculate reserves cannot be met. If conditions are not fully met, arbitrary applications of this method will result in serious deviation in the calculation [6]. In recent years, tremendous efforts have been spent in designing methods independent of formation compressibility, including the type curve match analysis and nonlinear regression methods. Table 1 indicates the scope of various types of information on this subject, listing the relevant papers that have been published in the petroleum literature.

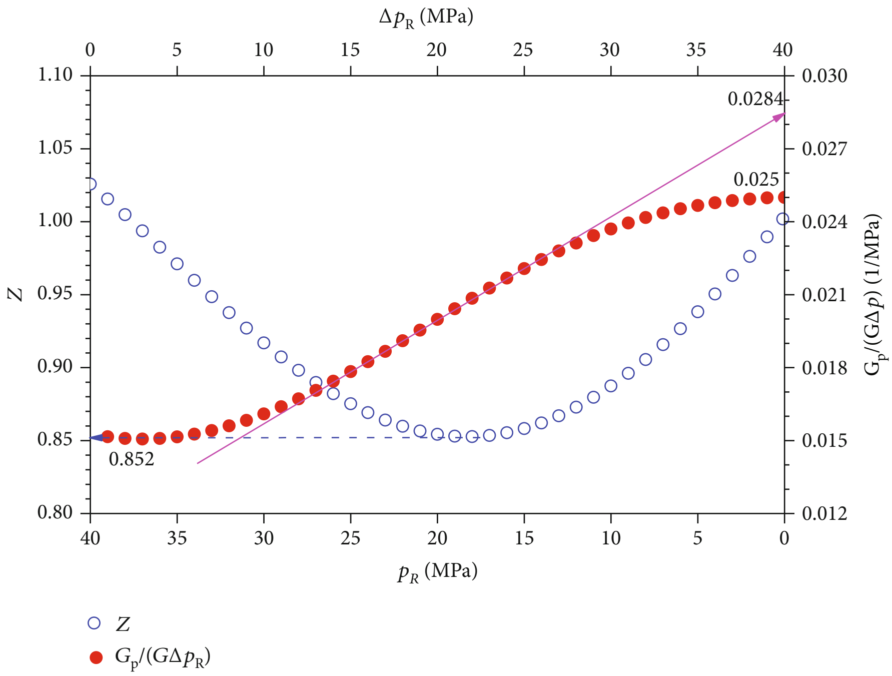
This has provided new solutions to the reserve estimate problem of a high pressure gas reservoir when the starting condition is met in the middle and late stages of development. However, a simple but practical method is still missing for the reserve estimate in the early development stage.

To bridge the gap, starting with the definition of formation compressibility and the material balance equation of volumetric gas reservoir, we established an analysis method for the reserve estimate based on gas production of cumulative unit pressure drop and evaluated its performance in three gas reservoirs.

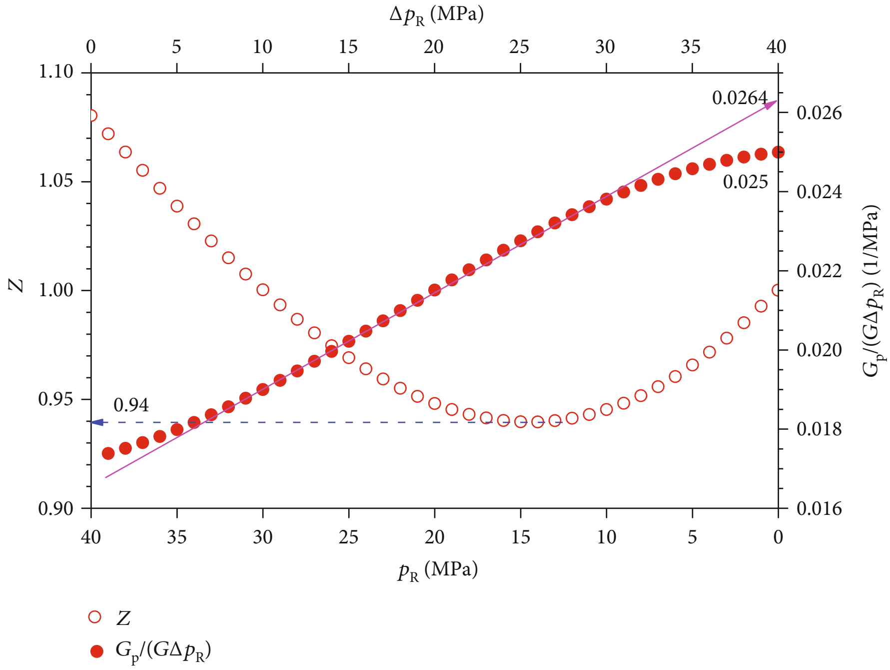
2. Gas Production of Cumulative Unit Pressure Drop

2.1. Isothermal Compressibility of Gas. In general, the isothermal coefficient of compressibility of a material is defined as

$$C_f = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T, \qquad (1)$$

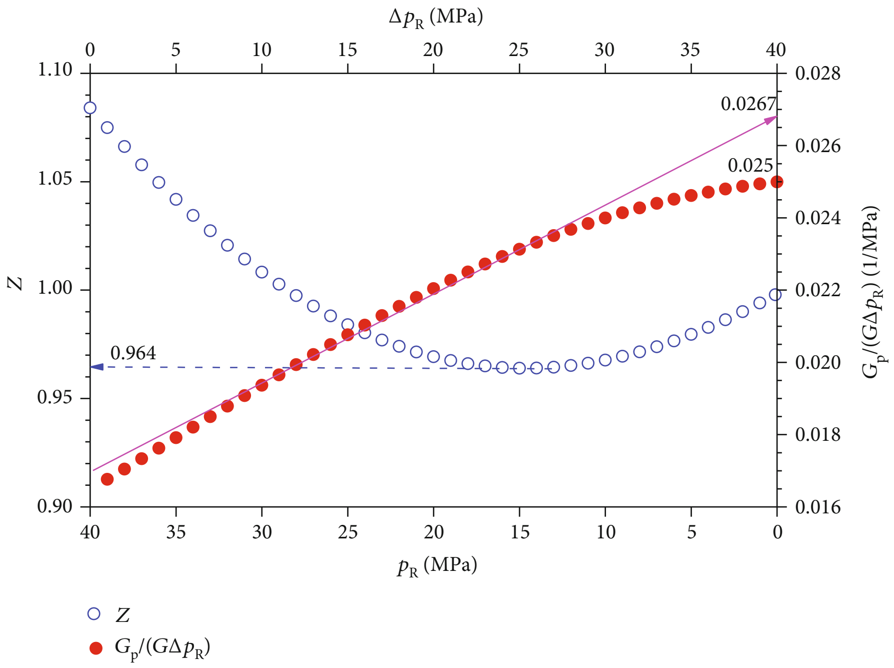


(a) 333.15 K



(b) 373.15 K

Figure 2: Continued.



(c) 413.15 K

FIGURE 2: Effect of temperature on gas production of cumulative pressure drop.

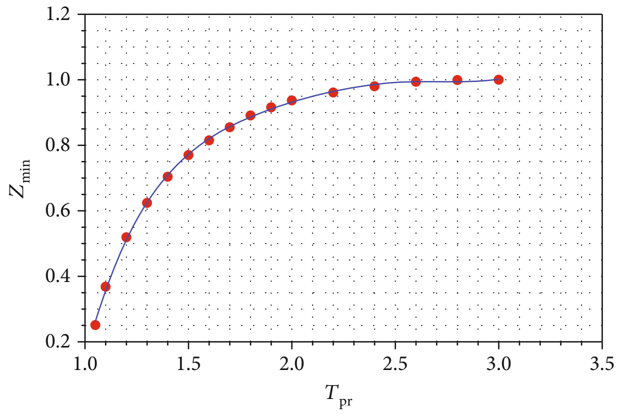


FIGURE 3: Minimum deviation factor at different pseudoreduced pressures.

where C_f denotes isothermal compressibility of gas in 1/MPa, with p denoting pressure in MPa and V denoting volume in 10^8 m^3.

2.2. Gas Production of Cumulative Pressure Drop. Gas production per unit pressure drop is defined as cumulative gas production per unit drop of average formation pressure. Gas production of cumulative unit pressure drop is defined as the ratio of cumulative gas production to cumulative drawdown of formation pressure from the initial formation pressure condition to the current formation pressure condition.

When equation (1) is applied to a gas reservoir,

$$C_f = -\frac{1}{G}\left(\frac{dG}{dp}\right)_T. \tag{2}$$

TABLE 2: Producing history of Anderson "L" gas reservoir (Duggan, 1972).

p	G_p	p/Z	Δp	$G_p/\Delta p$
MPa	10^8 m^3	MPa	MPa	10^8 m^3/MPa
65.548	0.000	45.52	0	0.0000
64.066	0.118	45.18	1.482	0.0796
61.846	0.492	44.59	3.702	0.1329
59.260	0.966	44.09	6.288	0.1536
57.447	1.276	43.65	8.101	0.1575
55.220	1.647	43.07	10.328	0.1595
52.421	2.257	42.31	13.127	0.1719
51.062	2.620	41.92	14.486	0.1809
48.277	3.146	41.05	17.271	0.1822
46.340	3.519	40.40	19.208	0.1832
45.057	3.827	39.98	20.491	0.1868
39.741	5.163	37.92	25.807	0.2001
32.860	6.836	33.63	32.688	0.2091
29.613	8.389	31.91	35.935	0.2334
25.855	9.689	29.02	39.693	0.2441
22.387	10.931	26.21	43.161	0.2533

When separation variables are integrated,

$$G_p = G\int_p^{p_i} C_f \, dp = \left[G\bar{C}_{-f}\right](p_i p), \tag{3}$$

where $[G\bar{C}_{-f}]$ is the gas production of cumulative unit pressure drop, 10^8 m^3/MPa. When the formation pressure drops to 0.101325 MPa, there is

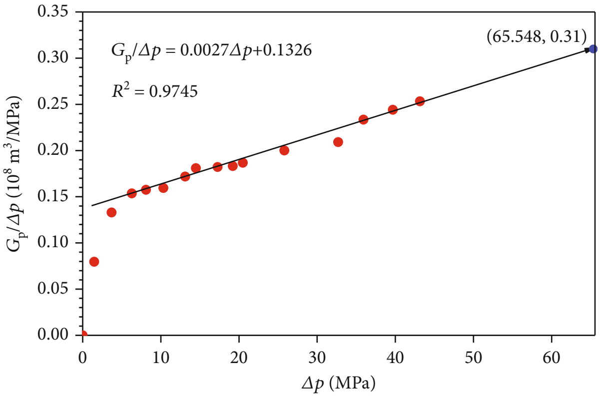


FIGURE 4: Reserves of Anderson "L" gas reservoir calculated by the method of gas production of cumulative unit pressure drop.

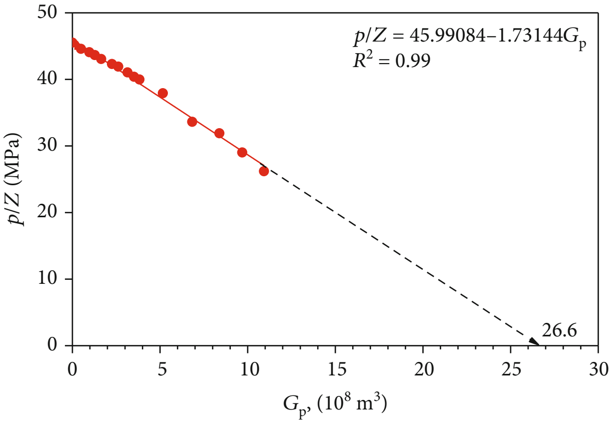


FIGURE 5: Reserves of Anderson "L" gas reservoir calculated by the p/Z curve method.

TABLE 3: Producing history of Louisiana offshore gas reservoir (Ramagost, 1981).

p	G_p	p/Z	Δp	$G_p/\Delta p$
MPa	10^8 m^3	MPa	MPa	10^8 m^3/MPa
78.903	0.000	52.743	0.000	0.0000
73.595	2.809	51.178	5.309	0.5291
69.851	8.104	50.000	9.053	0.8952
63.797	15.178	47.968	15.106	1.0047
59.116	21.994	46.184	19.788	1.1115
54.510	28.719	44.317	24.394	1.1773
50.883	34.082	42.687	28.020	1.2163
47.208	41.062	40.908	31.695	1.2955
44.044	45.485	39.255	34.860	1.3048
40.176	51.633	37.062	38.728	1.3332
37.294	55.991	35.283	41.610	1.3456
34.474	61.068	33.372	44.430	1.3745
31.026	66.754	30.872	47.877	1.3943
28.751	69.631	29.100	50.152	1.3884

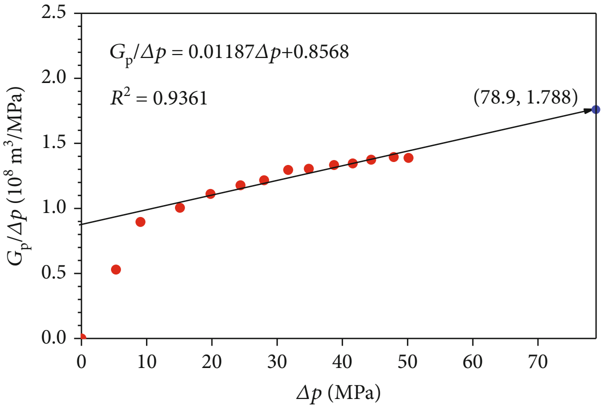


FIGURE 6: Reserves of Louisiana offshore gas reservoir calculated by the method of gas production of cumulative unit pressure drop.

$$G_p = G = \left[G\bar{C}_{-f}\right]p_i, \tag{4}$$

i.e., when the formation pressure drops to normal atmospheric pressure, the dimensionless gas production of the cumulative unit pressure drop is the reciprocal of the initial formation pressure.

2.3. Variation Law of Gas Production of Cumulative Unit Pressure Drop. The material balance equation of a volumetric gas reservoir can be expressed as

$$\frac{p}{Z} = \left(\frac{p}{Z}\right)_i \left(1 - \frac{G_p}{G}\right), \tag{5}$$

where p is the pressure, MPa; G_p is the cumulative gas production, 10^8 m^3; G is the reserves, 10^8 m^3; and the subscript i represents the initial state. Equation (5) is deformed, and the dimensionless cumulative gas production is

$$\frac{G_p}{G} = 1 - \frac{p/Z}{(p/Z)_i}. \tag{6}$$

When the pressure drops top_j, the dimensionless cumulative gas production is

$$\left(\frac{G_p}{G}\right)_j = 1 - \frac{(p/Z)_j}{(p/Z)_i}. \tag{7}$$

When the pressure drops top_{j+1}, the dimensionless gas production is

$$\left(\frac{G_p}{G}\right)_{j+1} = 1 - \frac{(p/Z)_{j+1}}{(p/Z)_i}. \tag{8}$$

The dimensionless gas production per unit pressure drop (assuming $p_j - p_{j+1} = 1$) is

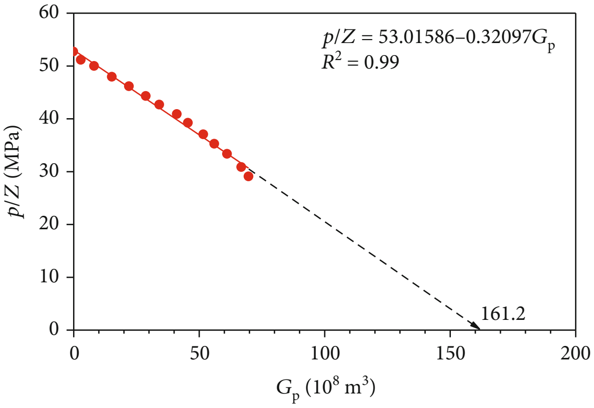


Figure 7: Reserves of Louisiana offshore gas reservoir calculated by the p/Z curve method.

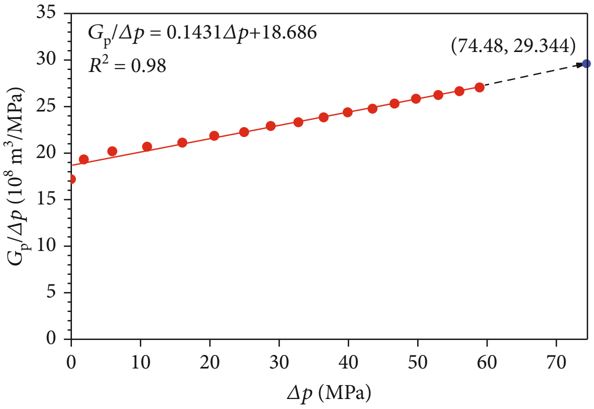


Figure 8: Reserves of X gas reservoir calculated by the method of gas production of cumulative unit pressure drop.

Table 4: Producing history of X gas reservoir.

p	G_p	p/Z	Δp	$G_p/\Delta p$
MPa	10^8 m^3	MPa	MPa	10^8 m^3/MPa
74.48	0.00	53.06	0	0
74.33	2.58	53.01	0.15	17.20
72.67	34.96	52.42	1.81	19.31
68.55	119.74	50.95	5.93	20.19
63.53	226.48	49.13	10.95	20.68
58.45	338.60	47.18	16.03	21.12
53.84	451.04	45.25	20.64	21.85
49.53	555.25	43.26	24.95	22.25
45.70	659.46	41.29	28.78	22.91
41.71	763.96	39.01	32.77	23.31
38.06	868.17	36.69	36.42	23.84
34.59	972.38	34.24	39.89	24.38
31.01	1076.59	31.47	43.47	24.77
27.83	1181.08	28.79	46.65	25.32
24.73	1285.29	25.98	49.75	25.83
21.52	1389.50	22.89	52.96	26.24
18.46	1493.16	19.78	56.02	26.65
15.55	1593.89	16.72	58.93	27.05

$$\left(\frac{G_p}{G}\right)_{j+1} - \left(\frac{G_p}{G}\right)_j = \frac{(p/Z)_j}{(p/Z)_i} - \frac{(p/Z)_{j+1}}{(p/Z)_i}. \qquad (9)$$

The dimensionless gas production of cumulative unit pressure drop is

$$\frac{(G_p/G)_j}{p_i - p_j} = \frac{1 - (p/Z)_j/(p/Z)_i}{p_i - p_j}. \qquad (10)$$

The theoretical calculation results show that with the depletion of formation pressure, affected by the deviation factor, the gas production per unit pressure drop first increases and then decreases, while the dimensionless gas production of cumulative unit pressure drop increases gradually. When the formation pressure drops to atmospheric pressure, its value is the reciprocal of the initial formation pressure, as shown in Figure 1.

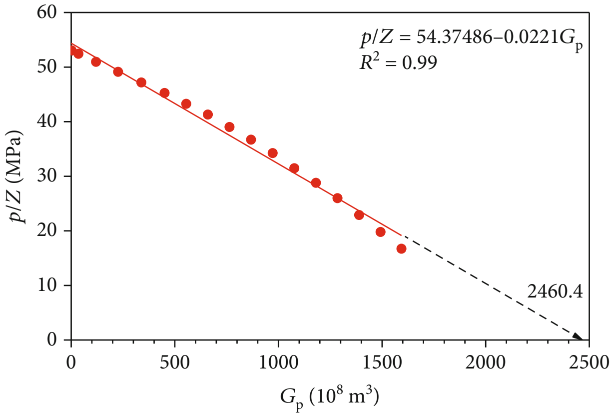


Figure 9: Reserves of X gas reservoir calculated by the p/Z method.

Figure 2 shows the variation of gas production of cumulative unit pressure drop with the drop of formation pressure at different temperatures, when the formation pressure is 40 MPa and the gravity of gas is 0.6. The relation curve of gas production of cumulative unit pressure drop and cumulative pressure drop is linear at early and middle stages; when the linear relation is prolonged to intersect with the vertical axis, the ratio a of gas production of cumulative unit pressure drop to intersection value is approximately equal to the minimum deviation factor. In Figure 2(a), the temperature is 333.15 K, $a = 0.025/0.0284 = 0.88 \approx 0.85$, and the relative error is 3.6%; in Figure 2(b), the temperature is 373.15 K, $a = 0.025/0.0264 = 0.95 \approx 0.94$, and the relative error is 1.1%; in Figure 2(c), the temperature is 413.15 K, $a = 0.025/0.0267 = 0.94 \approx 0.96$, and the relative error is 2.1%.

2.4. Minimum Deviation Factor of Natural Gas. The minimum deviation factor of natural gas depends on the pseudocritical property [22], as shown in Figure 3. When the pseudoreduced temperature is more than 1.9, the minimum deviation factor of natural gas is above 0.90.

Table 5: Comparison of reserves calculated by different methods.

Gas reservoir	Volumetric method reserves (10^8 m^3)	Reserves (10^8m^3)			
		p/Z curve method	Nonlinear regression method	Semilog type curve match method	Method introduced in the paper
Anderson "L"	19.68	26.6	19.9	20.0	19.0
Louisiana offshore	131.6	161.2	125.3	130.0	131.2
X	2091.5	2460.4	2032.0	2000.0	2032.55

When the pseudoreduced temperature is unknown, it can be calculated based on the gravity of natural gas, as given by

$$T_{\mathrm{pc}} = \frac{168 + 325\gamma_{\mathrm{g}} - 12.5\gamma_{\mathrm{g}}^2}{1.8}. \quad (11)$$

2.5. Calculation Method of Reserves. To sum up, the Cartesian plot of gas production of the cumulative unit pressure drop and the cumulative pressure drop is drawn, the linear regression is carried out, the straight line is prolonged to intersect with the vertical axis (as shown in Figure 2), and the product of the intersection ordinate value and the minimum deviation factor gives the reserve.

3. Case Analysis

3.1. Small Ultrahigh Pressure Gas Reservoir: Anderson "L" Gas Reservoir. The basic parameters of the American Anderson "L" gas reservoir [23] are as follows: the buried depth is 3404.5 m, the pressure coefficient is 1.907 MPa/100 m, the initial pressure is 65.55 MPa, the temperature is 403 K, the gravity of natural gas is 0.656, and the volumetric reserves are 19.68 × 10^8 m^3, with the producing history listed as in Table 2.

The relation curve of the cumulative pressure drop and the gas production of the cumulative unit pressure drop is given in Figure 4; linear regression is carried out for the data points, the straight line is prolonged to intersect with the vertical axis, and the intersection ordinate value is 0.31 × 10^8 m^3/MPa, which is multiplied by the initial formation pressure 65.548 MPa, and the reserve is obtained as 20.29 × 10^8 m^3. The minimum deviation factor is 0.935 based on Figure 3. Therefore, the reserves of the gas reservoir is estimated as 20.29 × 0.935, i.e., 19.00 × 10^8 m^3. The reserves calculated by this method are 3.5% smaller than that by the volumetric method. The p/Z curve method, which gave an estimation of 26.6 × 10^8 m^3, is shown in Figure 5.

3.2. Medium Ultrahigh Pressure Gas Reservoir: Louisiana Offshore Gas Reservoir. The basic parameters of the American Louisiana offshore ultrahigh pressure gas reservoir [23] are as follows: the buried depth is 4055 m, the pressure coefficient is 1.95 MPa/100 m, the initial pressure is 78.903 MPa, the temperature is 401.55 K, the gravity of the natural gas is 0.60, the pseudoreduced temperature is 1.96, the initial water saturation is 0.22, and the reserves are 131.6 × 10^8 m^3, with the producing history listed as in Table 3.

The relation curve of the cumulative pressure drop and gas production of the cumulative unit pressure drop is given in Figure 6. The intersection ordinate value is 1.788 × 10^8 m^3/MPa, which is multiplied by the initial formation pressure 78.903 MPa leading to the reserves of 141.07 × 10^8 m^3. The pseudoreduced temperature of the gas reservoir is 1.96, and the minimum deviation factor is 0.93. Therefore, the reserve of the gas reservoir is 141.07 × 0.93, i.e., 131.2 × 10^8 m^3. The reserves calculated by this method are highly consistent with that calculated by the dynamic method in the references [9]. If the reserves are calculated directly by the p/Z curve method, the calculated results are 161.2 × 10^8 m^3, as shown in Figure 7, which are much larger than the values calculated by the new method.

3.3. Large High Pressure Gas Reservoir: X Gas Reservoir. The basic parameters of the X gas reservoir [16] are as follows: the middle buried depth is 3750 m, the pressure coefficient is 2.0 MPa/100 m, the initial formation pressure is 74.48 MPa, the minimum deviation factor is 0.93, and the reserves calculated by the volumetric method are 2091.5 × 10^8 m^3, with the producing history listed as in Table 4.

The relation curve of the cumulative pressure drop and gas production of the cumulative unit pressure drop is given in Figure 8. The intersection ordinate value is 29.344 × 10^8 m^3/MPa, which is multiplied by the initial formation pressure 74.48 MPa leading to the reserves of 2185.54 × 10^8 m^3. The minimum deviation factor is 0.93. Therefore, the reserve of the gas reservoir is 2185.54 × 0.93, i.e., 2032.55 × 10^8 m^3, which is 2.8% lower than the reserves calculated by the volumetric method. If the reserves are calculated directly by the p/Z method, the calculated result is 2460.4 × 10^8 m^3, as shown in Figure 9, which is 17.6% higher than the reserves calculated by the static method.

3.4. Comparison with Calculated Results of Other Methods without Considering Formation Compressibility. As seen in Table 5, the calculated results of the method introduced in the paper are close to those of the nonlinear regression method and the semilogarithmic type curve match method, and the three cases further verify the correctness of the method. When the gas reservoir is in the early stage of development and there is no obvious inflection point in the p/Z curve, this method can be used to approximately estimate the reserves of the gas reservoir.

4. Conclusions and Suggestions

(1) Since it is difficult to accurately determine the formation compressibility in the material balance equation of high pressure gas reservoirs, the method without

considering the formation compressibility is recommended for reserve estimation

(2) When the formation pressure drops to the normal atmospheric pressure, the dimensionless gas production of the cumulative unit pressure drop is the reciprocal of the initial formation pressure. The relation curve of the dimensionless gas production of the cumulative unit pressure drop and pressure drop is a straight line in the medium term. The reserve correction coefficient is related to temperature

(3) The method of gas production of cumulative unit pressure drop, the semilog curve match analysis technique, and the nonlinear regression method can be used in turn to calculate the reserves based on the length of production time. If the production time is short, the reserves can be roughly estimated by the method of gas production of the cumulative unit pressure drop. Based on the reserve estimate results, combined with material balance equation, the effective compressibility coefficient can be calculated, and then, the water influx can be calculated

(4) For the water drive gas reservoir, the reserves calculated by the method of gas production of the cumulative unit pressure drop are relatively optimistic; in the future, the evaluation method of water drive gas reservoirs should be further studied to reduce the ambiguity of analysis results

Data Availability

Previously reported data were used to support this study and are available at [doi:10.2118/10125-MS; doi:10.1016/j.ijhydene.2017.04.190; doi:10.2118/2938-PA]. These prior studies (and datasets) are cited at relevant places within the text as references [9, 16, 23].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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