A New Method to Calculate the Recoverable Reserves and Recovery Ratio of Shale Gas Reservoir

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Abstract

At present, the most commonly used method to calculate recoverable reserves of shale gas reservoirs is the production decline curve method, which is only applicable to the production wells with decreasing production. For the production wells with constant productions, the material balance method could be used to calculate the recoverable reserves, but it does not consider the particularity of shale gas reservoirs. Under this circumstance, this paper deduces a new calibration method for recoverable reserves of shale gas reservoirs with double porosity medium. The method is based on the material balance equation, which has a wide application range. The method cannot only calculate the recoverable reserves and recoveries of free gas in fractures, but also calculate recoverable reserves and recoveries of free gas and adsorbed gas in the matrix. The calculated results show that the free gas in the shale gas reservoir is mainly in the fractures. The recovery of the free gas in the fractures is relatively high and the recovery of the free gas and adsorbent gas in the matrix is rather low. Gas reservoir recovery and recoverable reserves are more sensitive to abandonment pressure, therefore, in the production process, the reduction of the abandonment pressure of gas reservoir should be attempted. The matrix porosity, the adsorption phase density and the crack compression coefficient have a greater effect on the recovery rate. And the study of these parameters needs to be strengthened in order to obtain more accurate parameters.

1. Introduction

Shale gas reservoir is a kind of unconventional reservoir where the natural gas is

stored in the dark shale or high-carbon shale and it is a typical *in-situ* accumulated reservoir [1]. The natural gas is stored in the reservoir formation in the form of free gas and adsorbed gas. Free gas is mainly distributed in the fracture pores and the matrix pores, while the adsorbed gas is mainly distributed on the inner surface of micro-porous matrix system [2]. Chen proposed pressure decline method, material balance method, and production decline method to calculate the conventional gas reservoir recoverable reserves [3]. Chen used the principle of material balance to obtain the recoverable reserves of coalbed gas reservoir with constant volume [4]. However, the methods are not applicable for shale gas reservoirs as status of gas in the coalbed gas reservoirs is different from that of shale gas reservoirs. Ilk proposed an exponential law reduction method that can be used to calculate the recoverable reserves of shale gas reservoirs [5]. Valko proposed an extended exponential reduction method for shale gas reservoirs, which is an empirical method [6]. Duong proposed empirical analysis of the decline in gas production in fractured shale gas reservoirs and calculated recoverable reserves using this method [7]. Duan found that the use of power-law exponential decay methods in the early production of gas wells can predict gas production, recoverable reserves and declining rates [8]. Bai found that shale gas production decline curve can be used to learn most of the hyperbolic decline [9]. Chen introduced the hyperbolic yield reduction model to predict recoverable reserves of shale gas reservoirs [10]. Cao predicted the recoverable reserves of shale gas reservoirs by using a power law exponential diminution model [11].

The widely used recoverable reserves calculation method now is the pressure drop method and the production decline curve method. But the pressure drop method does not consider the particularity of the shale gas reservoir. Thus, the production decline curve method is only applicable to the well with gradually decrease output and it is only an empirical method. Therefore, from the view of mass conservation, this paper establishes the material balance equation of shale gas reservoir, using the equation the controlled reserves, the recoverable reserves and recovery rate could be obtained when the formation pressure reaches the abandonment pressure. Moreover, this paper can calculate the recovery of free gas in the matrix, free gas in the cracks and adsorbed gas in the matrix which does not require the production data and pressure data. It is very convenient for low porosity and low permeability shale gas reservoirs.

2. Methods

The development of the shale gas reservoir is an isothermal process, so the shale gas adsorption isotherm [12] is Equation (1).

$$V_E = \frac{V_L p}{p_L + p} \tag{1}$$

Adsorption gas is mainly adsorbed on the pore surface of the shale matrix [13], which will cause that the pore size occupied by the gas is smaller than the actual pore size. Ambrose [14] and Cao [15] define the apparent porosity of the

adsorption phase, which is shown in Equation (2).

$$\phi_a = 4.6545 \times 10^{-5} M \frac{\rho_h}{\rho_s} \left(V_L \frac{p}{p + p_L} \right) \tag{2}$$

The reserves of free gas in the matrix at the initial formation pressure can be expressed as Equation (3).

$$G_{mi} = \frac{V_m \left[\phi_{mi} \left(1 - s_{mwi} \right) - \phi_{ai} \right]}{B_{gi}} \tag{3}$$

At initial formation pressure, the reserves of free gas in the fracture can be expressed as Equation (4).

$$G_{fi} = \frac{V_{fp} \left(1 - s_{fwi} \right)}{B_{gi}} \tag{4}$$

At the initial formation pressure, the reserves of adsorbed gas in the matrix are Equation (5).

$$G_{ai} = V_m \rho_h V_{Ei} \tag{5}$$

When the formation pressure decreases and desorption of the adsorbed gas takes place, the shale matrix shrinks and deforms which cause the increase of the matrix porosity. When the fluid flows out, the effective stress increases and the rock skeleton volume is compressed, which cause the matrix porosity to decrease. Therefore, the matrix porosity is affected by the effects of both shrinkage of matrix and increase of stress [16].

The relationship between rock deformation and reservoir formation pressure could be explained by the Bangham [17] solid deformation theory and the Langmuir isothermal adsorption model, which is shown in Equation (6).

$$\Delta \varepsilon = \frac{\rho_h RTV_L}{EV_0} \times \left[\ln \left(p_L + p_i \right) - \ln \left(p_L + p \right) \right] \tag{6}$$

The total deformation of the shale matrix is the sum of the matrix shrinkage and the elastic expansion of the rock, as shown in Equation (7).

$$\Delta \varepsilon_z = \frac{\rho_h RTV_L}{EV_0} \times \left[\ln \left(p_L + p_i \right) - \ln \left(p_L + p \right) \right] - c_m \left(p_i - p \right) \tag{7}$$

Seidle (1985) [18] proposed an equation to explain the relationship between the matrix porosity and the deformation of the matrix, which is shown in Equation (8).

$$\frac{\phi_m}{\phi_{mi}} = 1 + \left(1 + \frac{2}{\phi_{mi}} \right) \left\{ \frac{\rho_h RTV_L}{EV_0} \times \left[\ln \left(p_L + p_i \right) - \ln \left(p_L + p \right) \right] - c_m \left(p_i - p \right) \right\} \tag{8}$$

So the matrix porosity after deformation can be obtained from Equation (9).

$$\phi_m = \left\{ 1 + \left(1 + \frac{2}{\phi_{mi}} \right) \left\{ \frac{\rho_h RTV_L}{EV_0} \times \left[\ln \left(p_L + p_i \right) - \ln \left(p_L + p \right) \right] - c_m \left(p_i - p \right) \right\} \right\} \phi_{mi} \tag{9}$$

As the pressure decreases, the rock particles deform and the initial water ex-

pands, and the change in the pore volume [19] in the fracture is given by Equation (10).

$$\Delta V = V_{fp}\left[\left(c_f + c_w s_{fwi}\right)\left(p_i - p\right)\right] \tag{10}$$

The definition of the coefficient of compressibility can be shown in Equation (11).

$$c_{mx} = -\frac{1}{V_{mp}}\frac{\Delta V_{mp}}{\Delta p} = \frac{\phi_{mi} - \phi_m}{\phi_{mi}\left(p_i - p\right)}$$
$$= \left(1 + \frac{2}{\phi_i}\right)\left\{\frac{\rho_h RTV_L}{EV_0\left(p_i - p\right)} \times \left[\ln\left(p_L + p\right) - \ln\left(p_L + p_i\right)\right] + c_m\right\} \tag{11}$$

Based on the elastic deformation of matrix rock particles and initial water [20], the material equilibrium equation of formation water is shown in Equation (12).

$$V_{mp}\left[1 - c_{mx}\left(p_i - p\right)\right]s_{mw} = V_{mp}s_{mwi} + V_{mp}c_w s_{mwi}\left(p_i - p\right) \tag{12}$$

The irreducible water saturation in the matrix at the present formation pressure is shown in Equation (13).

$$s_{mw} = \frac{s_{mwi}\left[1 + c_w\left(p_i - p\right)\right]}{1 - c_{mx}\left(p_i - p\right)} \tag{13}$$

At the present formation pressure, the residual reserves of adsorbed gas in the matrix is Equation (14).

$$G_{ar} = V_m \rho_h V_E \tag{14}$$

At the present formation pressure, the residual free gas reserves in the matrix can be expressed as Equation (15).

$$G_{mr} = \frac{V_m\left[\phi_m\left(1 - s_{mw}\right) - \phi_a\right]}{B_g} \tag{15}$$

At the present formation pressure, the residual free gas reserves in the fracture type can be shown in Equation (16).

$$G_{fr} = \frac{V_{fp}\left(1 - s_{fwi}\right) - \Delta V}{B_g} \tag{16}$$

From the conservation of mass, The sum of the original matrix free gas reserves, the original crack free gas reserves, the original matrix adsorbed gas reserves is equal to the sum of the remaining free reserves of the matrix, the remaining free reserves of the fissures, the residual gas reserves of the matrix and the cumulative production.

So the Equation (17) can be obtained when the Equations (3), (4), (5), (10), (14), (15) and (16) are obtained.

$$G_p = \frac{V_{fp}\left(1 - s_{fwi}\right)}{B_{gi}} + \frac{V_m\left[\phi_{mi}\left(1 - s_{mwi}\right) - \phi_{ai}\right]}{B_{gi}} + V_m\rho_h V_{Ei} - V_m\rho_h V_E$$
$$- \frac{V_m\left[\phi_m\left(1 - s_{mw}\right) - \phi_a\right]}{B_g} - \frac{V_{fp}\left(1 - s_{fwi}\right) - V_{fp}\left[\left(c_f + c_w s_{fwi}\right)\left(p_i - p\right)\right]}{B_g} \tag{17}$$

Then the Equation (18) can be deduced.

$$G_p = V_{fp} \left(\frac{(1-s_{fwi})}{B_{gi}} - \frac{(1-s_{fwi})}{B_g} + \frac{(c_f + c_w s_{fwi})(p_i - p)}{B_g} \right)$$
$$+ V_m \left(\frac{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]}{B_{gi}} + \rho_h V_{Ei} - \rho_h V_E - \frac{\left[\phi_m (1-s_{mw}) - \phi \right]}{B_g} \right)$$

(18)

Substituting Equations (3) and (4) into Equation (18) will deduce Equation (19).

$$G_p = \frac{G_{fi} B_{gi}}{(1-s_{fwi})} \left(\frac{(1-s_{fwi})}{B_{gi}} - \frac{(1-s_{fwi})}{B_g} + \frac{(c_f + c_w s_{fwi})(p_i - p)}{B_g} \right)$$
$$+ \frac{G_{mi} B_{gi}}{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]} \left(\frac{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]}{B_{gi}} + \rho_h V_{Ei} - \rho_h V_E - \frac{\left[\phi_m (1-s_{mw}) - \phi_a \right]}{B_g} \right)$$

(19)

Now some symbols can be defined to simplify the Equation (19).

$$F = \frac{B_{gi}}{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]} \left(\frac{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]}{B_{gi}} + \rho_h V_{Ei} - \rho_h V_E - \frac{\left[\phi_m (1-s_{mw}) - \phi_a \right]}{B_g} \right)$$

$$Y = G_p$$

$$M = \frac{B_{gi}}{(1-s_{fwi})} \left(\frac{(1-s_{fwi})}{B_{gi}} - \frac{(1-s_{fwi})}{B_g} + \frac{(c_f + c_w s_{fwi})(p_i - p)}{B_g} \right)$$

(20)

Substituting Equation (20) into Equation (19), the Equation (21) can be deduced.

$$\frac{Y}{M} = G_{fi} + G_{mi} \frac{F}{M}$$

(21)

From the above equations, a straight curve could be obtained if the value of Y/M is plotted against F/M in the Cartesian coordinate system. The intercept of this curve is the free gas reserves in the fracture and the slope of this curve is the free gas reserves in the matrix. The total reserves controlled could be expressed by Equation (22).

$$G = G_{fi} + G_{mi} + \frac{G_{mi} B_{gi}}{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]} \rho_h V_{Ei}$$

(22)

When the formation pressure reaches the abandonment pressure, the well is shut down and the production is stopped. The cumulative production amount at this time is the recoverable reserves of the reservoir. Substituting Equations (3), (4) and (5) into Equation (17) will yield Equation (23).

$$G_p = \frac{G_{mi} B_{gi}}{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]} \left(\frac{\left[\phi_{mi}(1-s_{mwi}) - \phi_{ai} \right]}{B_{gi}} - \frac{\left[\phi_m (1-s_{mw}) - \phi_a \right]}{B_g} \right)$$
$$+ \frac{G_{fi} B_{gi}}{(1-s_{fwi})} \left(\frac{(1-s_{fwi})}{B_{gi}} - \frac{(1-s_{fwi})}{B_g} + \frac{(c_f + c_w s_{fwi})(p_i - p)}{B_g} \right) + \frac{G_{ai}}{\rho_h V_{Ei}} (\rho_h V_{Ei} - \rho_h V_E)$$

(23)

And because the volume factor of the gas at present formation pressure can

be expressed by Equation (24).

$$B_{g} = \frac{zTp_{sc}}{z_{sc}T_{sc}p} \tag{24}$$

When the formation pressure reaches the abandonment pressure, substituting Equations (1) and (24) into Equation (23) will yield Equation (25).

$$G_{R} = G_{mi}\left(1 - \frac{\left[\phi_{m}\left(1 - s_{mw}\right) - \phi_{a}\right]}{\left[\phi_{mi}\left(1 - s_{mwi}\right) - \phi_{ai}\right]}\frac{p_{a}/z_{a}}{p_{i}/z_{i}}\right)$$
$$+ G_{fi}\left(1 - \frac{p_{a}/z_{a}}{p_{i}/z_{i}}\left(1 - \frac{\left(c_{f} + c_{w}s_{fwi}\right)\left(p_{i} - p_{a}\right)}{\left(1 - s_{fwi}\right)}\right)\right) + G_{ai}\left(\frac{p_{L}}{p_{i}}\frac{p_{i} - p_{a}}{p_{L} + p_{a}}\right) \tag{25}$$

The recovery of free gas in the matrix can be expressed by Equation (26).

$$E_{Rm} = 1 - \frac{\left[\phi_{m}\left(1 - s_{mw}\right) - \phi_{a}\right]}{\left[\phi_{mi}\left(1 - s_{mwi}\right) - \phi_{ai}\right]}\frac{p_{a}/z_{a}}{p_{i}/z_{i}} \tag{26}$$

The recoverable reserves of free gas in the matrix can be expressed by Equation (27).

$$G_{Rm} = G_{mi}E_{Rm} \tag{27}$$

The recovery of free gas in the fracture can be expressed by Equation (28).

$$E_{Rf} = 1 - \frac{p_{a}/z_{a}}{p_{i}/z_{i}}\left(1 - \frac{\left(c_{f} + c_{w}s_{fwi}\right)\left(p_{i} - p_{a}\right)}{\left(1 - s_{fwi}\right)}\right) \tag{28}$$

The recoverable reserves of free gas in fractures can be expressed by Equation (29).

$$G_{Rf} = G_{fi}E_{Rf} \tag{29}$$

The recovery of adsorbed gas in the matrix can be expressed by Equation (30).

$$E_{Ra} = \frac{p_{L}}{p_{i}}\frac{p_{i} - p_{a}}{p_{L} + p_{a}} \tag{30}$$

The recoverable reserves of adsorbed gas in the matrix can be expressed by Equation (31).

$$G_{Ra} = G_{ai}E_{Ra} \tag{31}$$

3. Results

The basic formation parameters of a certain well of a shale gas reservoir are listed as follows.

$p_{i} = 24.13\,\text{MPa}$, $B_{gi} = 4.82 \times 10^{-3}$, $s_{mwi} = 0.25$, $c_{m} = 4.35 \times 10^{-4}\,\text{MPa}^{-1}$, $c_{f} = 2.04 \times 10^{-2}\,\text{MPa}^{-1}$, $c_{w} = 4.35 \times 10^{-4}\,\text{MPa}^{-1}$, $S_{fwi} = 0$, $\varphi_{i} = 0.112$, $V_{L} = 11.32\,\text{m}^{3}/\text{t}$, $p_{L} = 2.41\,\text{MPa}$, $\rho_{s} = 0.34\,\text{g}/\text{cm}^{3}$, $\rho_{h} = 2.65\,\text{g}/\text{cm}^{3}$, $E = 26800\,\text{MPa}$, $T = 366.49\,\text{K}$, $R = 8.134 \times 10^{-6}\,\text{MPa}/(\text{K}\cdot\text{mol})$, $V_{0} = 0.0245\,\text{m}^{3}/\text{mol}$, $M = 20\,\text{g}/\text{mol}$, $p_{a} = 3\,\text{MPa}$

The production data are shown in Table 1.

Table 1. The production data for shale gas reservoir.

G_p (cumulative production) / 10^8 m^3	P (pressure) / MPa	B_g (the volume factor of the gas)/(m^3·m^{-3})
0.0000	24.13	0.0048
1.4357	21.37	0.0053
3.4847	17.24	0.0065
5.2855	13.79	0.0081
6.0276	12.41	0.0091
6.7830	11.03	0.0103
6.2137	8.45	0.0137
9.5728	6.34	0.0187
10.6503	4.83	0.0250
11.3299	4.01	0.0304

Based on the production data in Table 1, the single well reserve, recoverable reserve and recovery could be calculated by using the material balance equation (see Figure 1). The results are shown in Table 2.

Table 2. The results of controlled reserves.

Well	Free gas reserves in the matrix/10^8 m^3	Free gas reserves in fractures/10^8 m^3	Adsorption gas reserves/10^8 m^3	Total reserves, /10^8 m^3
Well X	0.7827	8.2981	11.0225	20.1033

Well	Free gas recovery in matrix /%	Free gas recovery in fractures /%	Adsorption gas recovery rate /%	Total recovery /%
Well X	56.06	93.37	39.04	62.13

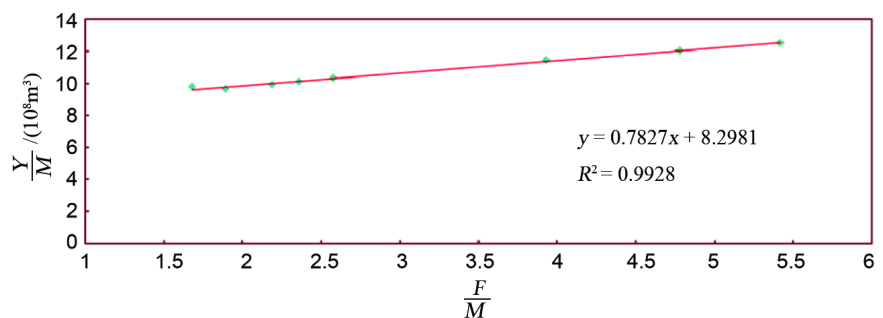| Well	Free gas recoverable reserves in matrix, /10^8 m^3	Free gas recoverable reserves in fractures/10^8 m^3	Adsorbed gas recoverable reserves/10^8 m^3	Total recoverable reserves/10^8 m^3
Well X	0.4388	7.7478	4.3030	12.4897

$$y = 0.7827x + 8.2981$$
$$R^2 = 0.9928$$

Figure 1. The results for this article using material balance equation.

Table 2 shows that the free gas mainly exists in the fractures, as the calculated recovery of free gas in the fracture is 93.37%, and the calculated recovery of free gas in the matrix is 56.06%. The calculated recovery of adsorbed gas in the matrix is the lowest, which is 39.04% and the total recovery of the gas is 62.13%.

Now assuming different abandonment pressures and calculating the recovery and recoverable reserves under different waste pressures, the results are shown in Table 3.

Table 3. The results of recovery for different abandonment pressure calculation.

Abandoned pressure /MPa	Free gas recovery in matrix/%	Free gas recovery in fractures/%	Adsorption gas recovery rate /%	Recovery ratio/%
2.8	57.43	93.87	40.92	63.42
2.6	58.91	94.37	42.95	64.80
2.4	60.51	94.86	45.15	66.27
2.2	62.24	95.33	47.54	67.84
2.0	64.13	95.80	50.15	69.54
Abandoned pressure /MPa	Free gas recoverable reserves in matrix /10^8 m^3	Free gas recoverable reserves in fractures /10^8 m^3	Adsorbed gas recoverable reserves /10^8 m^3	Total recoverable reserves /10^8 m^3
2.8	0.4495	7.7897	4.5104	12.7496
2.6	0.4611	7.8308	4.7343	13.0262
2.4	0.4736	7.8712	4.9768	13.3216
2.2	0.4872	7.9109	5.2404	13.6384
2.0	0.5020	7.9498	5.5278	13.9796

Table 3 shows the calculation results by applying different abandonment pressure and it could be observed that as the abandonment pressure decreases, both of the recovery of the gas and recoverable reserves increase, and they are sensitive to the abandonment pressure.

Assuming different matrix porosity, then the recovery, controlled reserves and recoverable reserves under different matrix porosity can be calculated. And the results are shown in Table 4.

Table 4. The calculation results of recovery for different matrix porosity.

Matrix porosity/f	Free gas recovery in matrix/%	Free gas recovery in fractures/%	Adsorption gas recovery rate/%	Recovery ratio/%
0.12	68.74	93.37	39.04	62.82
0.14	78.49	93.37	39.04	64.43
0.16	81.79	93.37	39.04	65.88
0.18	83.45	93.37	39.04	67.18
0.20	84.45	93.37	39.04	68.35
0.12	1.2348	8.0026	10.5850	19.8224

Continued

Matrix porosity/f	Free gas recovery in matrix/%	Free gas recovery in fractures/%	Adsorption gas recovery rate/%	Recovery ratio/%
0.14	2.2188	7.3615	9.6147	19.1950
0.16	3.0333	6.8333	8.7951	18.6617
0.18	3.7161	6.3924	8.0960	18.2045
0.12	0.8848	7.4719	4.1322	12.4529
0.14	1.7415	6.8733	3.7534	12.3682
0.16	2.4809	6.3801	3.4335	12.2945
0.18	3.1010	5.9685	3.1606	12.2301
0.20	3.6270	5.6207	2.9256	12.1733

Table 4 shows that with the increase of matrix porosity, the recovery of free gas in the matrix and the total recovery are increasing, while the recovery of free gas in the cracks and the recovery of adsorbed gas in the matrix are unchanged.

In addition, with the increase of matrix porosity, the controlled reserves of free gas in the matrix are increasing, the recoverable reserves of free gas in the matrix are increasing, the controlled reserves of free gas in the cracks are decreasing, the recoverable reserves of free gas in the cracks are also decreasing, the controlled reserves of the adsorbed gas in the matrix are decreasing, the recoverable reserves of the adsorbed gas in the matrix are decreasing, the total controlled reserves are reduced and the total recoverable reserves are also reduced. Therefore, the porosity of the matrix not only affects free gas recovery in the matrix and total recovery, but also has a great influence on the calculated reserves and recoverable reserves of each part. But there are no effects on the recovery of free gas in the fracture and the recovery of adsorbed gas in the matrix.

Now assuming different density of the adsorption phase and calculating the recovery, controlled reserves and re-coverable reserves under different density of the adsorption phase, the results are shown in Table 5.

Table 5. The calculation results of recovery for different density of the adsorption phase.

Density of the adsorption phase/g·cm^{-3}	Free gas recovery in matrix/%	Free gas recovery in fractures/%	Adsorption gas recovery rate/%	Recovery ratio/%
0.40	76.15	93.37	39.04	63.47
0.45	80.42	93.37	39.04	64.28
0.50	82.54	93.37	39.04	64.88
0.55	83.80	93.37	39.04	65.37
0.60	84.64	93.37	39.04	65.76
0.40	1.6025	7.7038	10.2583	19.5646
0.45	2.0602	7.3724	9.8167	19.2492
0.50	2.4007	7.1279	9.4971	19.0257
0.55	2.6615	6.9404	9.2446	18.8465
0.60	2.8681	6.7920	9.0431	18.7032
0.40	1.2202	7.1929	4.0047	12.4178
0.45	1.6568	6.8835	3.8323	12.3726
0.50	1.9815	6.6552	3.7075	12.3443
0.55	2.2303	6.4801	3.6090	12.3195
0.60	2.4275	6.3416	3.5303	12.2994

Table 5 shows that with the increase of adsorption phase density, the recovery of free gas in the matrix and the total recovery are increasing, while the recovery of free gas in the cracks and the recovery of adsorbed gas in the matrix are un-changed.

In addition, with the increase of adsorption phase density, the controlled reserves of free gas in the matrix are in-creasing, the recoverable reserves of free gas in the matrix are increasing, the controlled reserves of free gas in the cracks are decreasing, the recoverable reserves of free gas in the cracks are also decreasing, the controlled reserves of the adsorbed gas in the matrix are decreasing, the recoverable reserves of the adsorbed gas in the matrix are decreasing, the total controlled reserves are reduced and the total recoverable reserves are also reduced.

Therefore, the density of the adsorption phase not only affects the free gas recovery in the matrix and total recovery, but also has a great influence on the calculated reserves and recoverable reserves of each part. But there are no effects on the recovery of free gas in the fracture and the recovery of adsorbed gas in the matrix.

Now assuming different coefficient of compressibility of the fracture and calculating the recovery, controlled re-serves and recoverable reserves under different coefficient of compressibility of the fracture, the results are shown in Table 6.

Table 6. The calculation results of recovery for different coefficient of compressibility of the fracture.

Coefficient of compressibility of the fracture/MPa^{-1}	Free gas recovery in matrix/%	Free gas recovery in fractures/%	Adsorption gas recovery rate/%	Recovery ratio/%
0.025	56.06	94.49	39.04	59.80
0.035	56.06	96.96	39.04	56.32
0.045	56.06	99.43	39.04	54.10
0.025	0.8936	7.6255	12.5843	21.1034
0.035	1.0813	6.4807	15.2276	22.7896
0.045	1.2175	5.6423	17.1457	24.0055
0.025	0.5010	7.2054	4.9127	12.6192
0.035	0.6062	6.2836	5.9446	12.8345
0.045	0.6826	5.6100	6.6934	12.9860

Table 6 shows that with the increase of coefficient of compressibility in the fracture, the recovery of free gas in the cracks is increasing, while the recovery of free gas in the cracks and the recovery of adsorbed gas in the matrix are un-changed, the total recovery is decreasing.

In addition, with the increase of coefficient of compressibility in the fracture, the controlled reserves of free gas in the matrix are increasing, the recoverable reserves of free gas in the matrix are increasing, the controlled reserves of free

gas in the cracks are decreasing, the recoverable reserves of free gas in the cracks are also decreasing, the controlled reserves of the adsorbed gas in the matrix are increasing, the recoverable reserves of the adsorbed gas in the matrix are increasing, the total controlled reserves are increasing and the total recoverable reserves are also increasing.

Therefore, the coefficient of compressibility in the fracture not only affects the free gas recovery in the cracks and total recovery, but also has a great influence on the calculated reserves and recoverable reserves of each part. But there are no effects on the recovery of free gas in the matrix and the recovery of adsorbed gas in the matrix.

4. Conclusions

In this paper, a calibration method of controlled reserves, recoverable reserves and recovery of shale gas reservoirs is established, which is widely applicable. It is shown from a realistic example that this method is simple and practically applicable. The calculated results show that the free gas in the shale gas reservoir mainly exists in the fracture and the proportion of the free gas in the matrix is small. But the adsorbed gas occupies most of the reserves. The recovery of adsorbed gas in the matrix is low, so in the later development, the matrix adsorption gas has great potential.

It also reveals that the recoverable reserves and recoveries are very sensitive to the abandonment pressure. Therefore, during the development process, the gas flow resistance should be minimized and the abandonment pressure should be reduced to obtain higher recovery and recoverable reserves. Besides, the porosity in matrix and the adsorption phase density affect the recovery of free gas in the matrix, and the fracture compression coefficient affects the recovery of free gas in the fracture. These three parameters have a significant effect on the calculation of reserves and recoverable reserves. Therefore, it is necessary to strengthen the study of these three parameters in future work in order to obtain more accurate values for the calculation of reserves.

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Nomenclature

p is the reservoir formation pressure, MPa;

p_i is the reservoir initial formation pressure, MPa;

V_E is the adsorption amount under the reservoir formation pressure, m^3/t;

V_L is the langmuir volume, m^3/t;

p_L is the langmuir pressure, MPa;

ϕ_a is the porosity of adsorption phase, f;

M is the molar weight, g/mol;

ρ_h is the density of the rock, g/cm^3;

ρ_s is the density of the adsorption phase, g/cm^3;

B_{gi} is the volume factor of the gas at the initial formation pressure, m^3/m^3;

s_{mwi} is the initial water saturation of the matrix at the initial formation pressure, f;

ϕ_{mi} is the matrix porosity at the initial formation pressure, f;

ϕ_{ai} is the porosity of adsorption phase at the initial formation pressure, f;

G_{mi} is the reserves of the free gas in the matrix at the initial formation pressure, 10^8 m^3;

V_m is the total volume of the matrix, 10^8 m^3;

s_{fwi} is the initial water saturation in the fracture, f;

G_{fi} is the reserves of free gas in the fracture at initial pressure, 10^8 m^3;

V_{fp} is the fracture pore volume, 10^8 m^3;

G_{ai} is the reserves of adsorbed gas at the initial formation pressure, 10^8 m^3;

V_{Ei} is the adsorption amount at the initial formation pressure, m^3/t;

$\Delta\varepsilon$ is the deformation of the rock caused by the desorption of gas, dimensionless;

R is the gas constant, MPa/(K·mol);

T is the temperature of the reservoir formation, K;

V_0 is the molar based specific volume, m^3/mol;

E is the Young's modulus, MPa;

$\Delta\varepsilon_z$ is the elastic expansion of the rock under effective stress and matrix shrinkage, dimensionless;

c_m is the elastic coefficient of compressibility for the rock, MPa^{-1};

ϕ_m is the matrix porosity after deformation;

ΔV is the change of the pore volume in the fracture, 10^8 m^3;

c_f is the coefficient of compressibility of the fracture, MPa^{-1};

c_w is the coefficient of compressibility of the irreducible water, MPa^{-1};

V_{mp} is the Matrix pore volume, 10^8 m^3;

s_{mw} is the saturation of bound water under pressure, f;

G_{ar} is the remaining reserves of adsorbed gas in the matrix at present formation pressure, 10^8 m^3;

G_{fr} is the remaining reserves of free gas in the fracture under present formation pressure, 10^8 m^3;

G_R is the recoverable reserves at abandoned pressure, 10^8 m^3;

B_g is the volume factor of the gas at present formation pressure, m^3/m^3;

p_a is the abandoned pressure, MPa;

E_{Rm} is the. recovery of free gas in matrix, f;

G_{Rm} is the recoverable reserves of free gas in the matrix, 10^8 m^3;

E_{Rf} is the recovery of free gas in fractures, f;

G_{Rf} is the recoverable reserves of free gas in fractures, 10^8 m^3;

G_{Ra} is the recoverable gas in the matrix, 108 m^3.