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Research Article

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A new form of material balance equation of condensate gas reservoir

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ABSTRACT

In calculation of reserves of gas reservoir, the material balance method is a kind of methods that currently use mostly and accurately. The condensate gas reservoir is a kind of complex special reservoirs, with the decline of formation pressure, retrograde condensate phenomenon will occur in the formation in the process of exploitation of gas reservoir, result in gas and liquid two phase, the change of reservoir fluid component and phase is very complex, this retrograde condensation feature makes the pressure drop of condensate gas reservoir not only relevant with the increase of things produced, but also some complex factors like retrograde condensation, especially the output quality of conversion between, namely the wellhead oil gas and bottom oil gas, with volume coefficient can not direct conversion, so the material balance equation are quite different from conventional gas reservoir. This paper established a material balance equation that can describe not only the release of elastic energy, but also the retrograde condensate phenomenon of condensate gas reservoir on the base of principle of mass conservation.

Key words: condensate gas reservoir, material balance equation, mass conservation, retrograde condensation

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INTRODUCTION

Gas reservoir material balance equation has been developing since 1940s. For the special and complicated characteristics of gas reservoir, there is complicated phase behavior variation companying with the condensate hydrocarbon fluid seepage during the exploitation, which would make a difference between condensate gas reservoir material balance equation and conventional gas reservoir. There are many experts have studied the material balance equation of condensate gas reservoir. Chen yuanqian [1] deduced gas reservoir material balance equation influenced by different driving pressure and applied the equation in condensate gas reservoir. During the calculation, the condensate oil should be converted into gas equivalently and the gross cumulative production is the sum of dry gas and condensate gas. The gas deviation factor is equal to the overall well fluid deviation factor; Ma yongxiang [2] developed the condensate gas reservoir material balance equation based on the molar weight balance theory. But he didn't illustrate the method about how to convert the gross oil volume into the gas volume. Qi zhilin et al. [3] established the general oil-rimming condensate gas reservoir material balance equation and he also didn't illustrate the method about how to convert the gross oil volume into the gas volume. According to the porous volume-balance fundamental principal of hydrocarbon, Chen yuxiang and Ma faming et al. [4] established the condensate gas reservoir material balance equation which considered the influences of fluid component and phase variation of the condensate gas reservoir. It also introduced the concept of condensate oil-volumetric factor and production GOR. For part of the gas phase will condensate into liquid phase in the process of fluid flowing from wellhead to bottom hole, the mass of oil and gas are changing. As a result, GOR of the wellhead is totally different from the GOR of the bottom hole; Yu yuanzhou and Yang guangrong et al. [5] improved the gas-injection condensate gas reservoir material balance equation. Considering the volume difference between injection gas and reservoir gas, single phase deviation factor or double phase deviation actor is used at different condition, and also, the volume of condensate oil is converted into the volume of gas. Kang xiaodong et al. [6] deduced the material equation for cyclic gas injection condensate gas reservoir which considering the composition-difference between injection gas and production gas;

Based on the molar weight balance principle, Li qian and Lixiangfang et al. [7] deduced the material balance equation for the abnormal pressure condensate gas reservoir under the condition of natural water drive, gas injection and oil rimming. But it has the same disadvantage as other equation.

At present times, although the condensate gas reservoir material balance equation considered the phase changing and the retrograde condensation in the condensate reservoir and all of them are on the basis of volume conservation or molar weight balance conversation, there is deviation in the calculation of cumulative production of condensate gas reservoir which converted condensate oil volume into gas volume. As a result, there is a significant deviation in calculation of condensate gas reservoir reserves and prediction of production performance. Therefore, considering the production characteristic of condensate reservoir, we developed the innovative material balance equation for the condensate reservoir based on the principle of mass conservation.

Derivation of the novel form

Although the volumes of oil and gas between formation condition and ground standard condition varied much, the total mass of oil and gas remained the same. On the basis of fundamental of mass conversation, this paper developed a generic form of mass balance equation for natural water driven condensate gas reservoir at gas injection condition. Assumed the original condensate gas in place was G, irreducible water saturation was Swi, so the volume of pore filled with gas was:

$$V_{\mathrm{p}} = \frac{GB_{\mathrm{gi}}}{1-S_{\mathrm{wi}}} \tag{1}$$

The initial water volume was:

$$V_{\mathrm{wc}} = \frac{S_{\mathrm{wi}}GB_{\mathrm{gi}}}{1-S_{\mathrm{wi}}} \tag{2}$$

The initial mass of condensate gas was:

$$m_{\mathrm{gci}} = \rho_{\mathrm{gi}}GB_{\mathrm{gi}} \tag{3}$$

The remained mass (including condensate gas and retrograde condensation oil) in place was:

$$m_{\mathrm{res}} = \rho_{\mathrm{gi}}GB_{\mathrm{gi}} - (\rho_{\mathrm{gsc}}G_{\mathrm{p}} + \rho_{\mathrm{osc}}N_{\mathrm{p}}) \tag{4}$$

According to PVT experiments, while the formation pressure decreased from Pi to P, the retrograde condensation oil saturation was So, then the reduced pore volume was:

$$\Delta V_{\mathrm{p}} = V_{\mathrm{p}}C_{\mathrm{p}}(P_{\mathrm{i}} - P) = \frac{C_{\mathrm{p}}GB_{\mathrm{gi}}(P_{\mathrm{i}} - P)}{1-S_{\mathrm{wi}}} \tag{5}$$

The total volume of irreducible water was：

$$V_{\mathrm{wc}} + \Delta V_{\mathrm{wc}} = V_{\mathrm{wc}} + V_{\mathrm{wc}}C_{\mathrm{w}}(P_{\mathrm{i}} - P) = \frac{S_{\mathrm{wi}}GB_{\mathrm{gi}}}{1-S_{\mathrm{wi}}} + \frac{C_{\mathrm{w}}S_{\mathrm{wi}}GB_{\mathrm{gi}}(P_{\mathrm{i}} - P)}{1-S_{\mathrm{wi}}} \tag{6}$$

If the volume of water influx was W_e, and the production volume of water was W_p, for gas reservoir would not exploited by water injection, so the pore volume filled with water influx was:

$$W = W_{\mathrm{e}} - W_{\mathrm{p}}B_{\mathrm{w}} \tag{7}$$

The volume of injection gas was:

$$V_{\mathrm{ip}} = G_{\mathrm{ip}}B_{\mathrm{gdr}} \tag{8}$$

The decreased of pore volume, expanded of irreducible water and water influx will lead to reducing the volume of the remained condensate gas in place. The remained gas volume in place while formation pressure decreased to P was:

$$
\begin{aligned}
&V_{\mathrm{res}} = V_{\mathrm{p}} - \Delta V_{\mathrm{p}} - V_{\mathrm{w}} - W - V_{\mathrm{ip}} = \\
&\frac{GB_{\mathrm{gi}}}{1-S_{\mathrm{wi}}} - \frac{C_{\mathrm{p}} GB_{\mathrm{gi}} (P_{\mathrm{i}} - P)}{1-S_{\mathrm{wi}}} - \frac{S_{\mathrm{wi}} GB_{\mathrm{gi}} + C_{\mathrm{w}} S_{\mathrm{wi}} GB_{\mathrm{gi}} (P_{\mathrm{i}} - P)}{1-S_{\mathrm{wi}}} - \left(W_{\mathrm{e}} - W_{\mathrm{p}} B_{\mathrm{w}}\right) - G_{\mathrm{ip}} B_{\mathrm{gdr}} \\
&= \left\{1 - \frac{C_{\mathrm{p}} + C_{\mathrm{w}} S_{\mathrm{wi}} (P_{\mathrm{i}} - P)}{1-S_{\mathrm{wi}}}\right\} GB_{\mathrm{gi}} - \left(W_{\mathrm{e}} - W_{\mathrm{p}} B_{\mathrm{w}}\right) - G_{\mathrm{ip}} B_{\mathrm{gdr}}
\end{aligned} \tag{9}
$$

The pore volume filled with retrograde condensation oil was:

$$
\Delta V_{\mathrm{o}} = S_{\mathrm{o}} V_{\mathrm{res}} \tag{10}
$$

The remained gas volume was:

$$
V_{\mathrm{g}} = (1 - S_{\mathrm{o}}) V_{\mathrm{res}} \tag{11}
$$

Substitution equation (9), (10), and (11) into equation (4) and simplified to:

$$
\begin{aligned}
&\rho_{\mathrm{gi}} GB_{\mathrm{gi}} - \left(\rho_{\mathrm{gsc}} G_{\mathrm{p}} + \rho_{\mathrm{osc}} N_{\mathrm{p}}\right) = \\
&\left\{[1 - \frac{\left(C_{\mathrm{p}} + C_{\mathrm{w}} S_{\mathrm{wi}}\right) \Delta P}{1-S_{\mathrm{wi}}}] GB_{\mathrm{gi}} - \left(W_{\mathrm{e}} - W_{\mathrm{p}} B_{\mathrm{w}}\right) - G_{\mathrm{ip}} B_{\mathrm{gdr}}\right\} [\rho_{\mathrm{g}} (1 - S_{\mathrm{o}}) + \rho_{\mathrm{o}} S_{\mathrm{o}}]
\end{aligned} \tag{12}
$$

Equation (12) was the novel form of mass balanced equation for natural water driven condensate gas reservoir at gas injection condition.

If there is no edge water and bottom water, equation (12) will changed into:

$$
\rho_{\mathrm{gsc}} G_{\mathrm{p}} + \rho_{\mathrm{osc}} N_{\mathrm{p}} = \rho_{\mathrm{gi}} GB_{\mathrm{gi}} - [1 - \frac{\left(C_{\mathrm{p}} + C_{\mathrm{w}} S_{\mathrm{wi}}\right) \Delta P}{1-S_{\mathrm{wi}}}] GB_{\mathrm{gi}} [\rho_{\mathrm{g}} (1 - S_{\mathrm{o}}) + \rho_{\mathrm{o}} S_{\mathrm{o}}] \tag{13}
$$

Equation (13) was the form of mass balanced equation for seal condensate gas reservoir.

If there no water influx and gas injection, equation (12) will changed into:

$$
\rho_{\mathrm{gi}} - \frac{\rho_{\mathrm{gsc}} G_{\mathrm{p}}}{GB_{\mathrm{gi}}} = \left[1 - \frac{\left(C_{\mathrm{p}} + C_{\mathrm{w}} S_{\mathrm{wi}}\right) \Delta P}{1-S_{\mathrm{wi}}}\right] \rho_{\mathrm{g}} \tag{14}
$$

Considering that:

$$
\rho = \frac{pM}{RTZ}, \quad B_{\mathrm{gi}} = \frac{p_{sc}}{T_{sc} Z_{sc}} \frac{T_i Z_i}{P_i} \tag{15}
$$

Equation (14) will be changed into:

$$
\frac{p_i}{Z_i}\left(1 - \frac{G_p}{G}\right) = \frac{p}{Z}[1 - \frac{C_p (P_i - P) + C_w S_{wi} (P_i - P)}{1 - S_{wi}}] \tag{16}
$$

Equation (16) was the form of mass balanced equation for seal dry gas reservoir

Case analysis

In order to confirm this novel form of mass balance equation, we take the M condensate gas reservoir in Tarim Oil field for example, using this new form to estimate the geological reserves.

Table 1: PVT datum of The Condensate Gas Reservoir

Formation Pressure: 50.98 MPa	Formation Temperature: 106.1 □
Dew Point Pressure: 47.83 MPa	Critical Pressure: 31.45 MPa
Land appear differential pressure: 3.15 MPa	Critical Temperature: -67.0 □
Critical Condensate Pressure: 49.47 MPa	Critical Condensate Temperature: 290.8 □
Volume Factor as Dew Point Pressure: 3.1983×10^{-3} m^3/m^3	Oil Density(20□): 0.7721 g/cm^3
Z-factor at Dew Point Pressure: 1.167	Molecular weight of oil: 153.95

The Z-factor and retrograde condensation oil volume at different pressure can be obtained from the results of constant mass expansion experiment and constant volume failure experiment. The density of gas and oil at different pressure can be calculated by state equations.

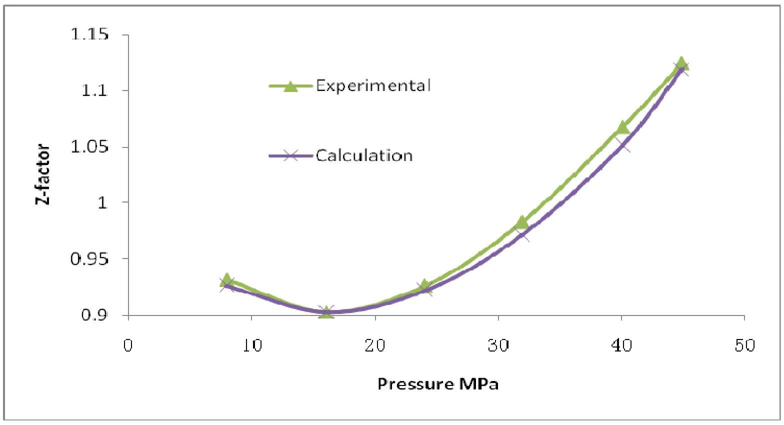

Fig.1: Z-factor vs. pressure

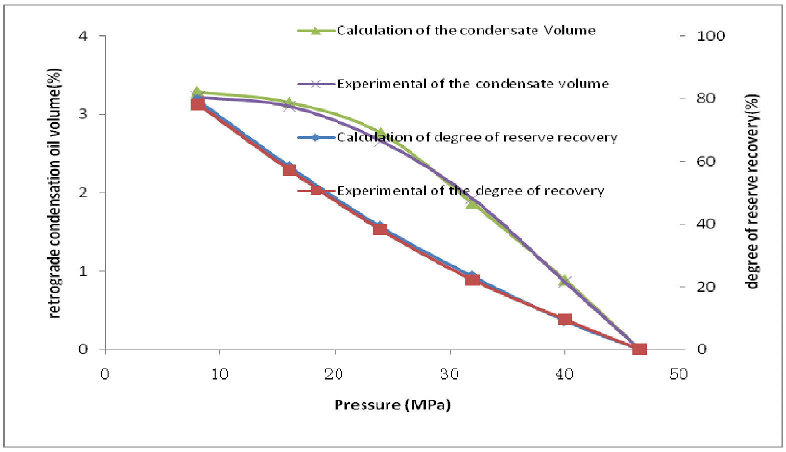

Fig.2: Retrograde condensation oil volume vs. pressure

Table 2: Physical Property of Oil and Gas at Different Pressure

Pressure (MPa)	Molar fraction (%)		Density (kg/m³)		Viscosity (mPa·s)		Relative permeability	
	Gas	Oil	Gas	Oil	Gas	Oil	Gas	Oil
51.01	1	0	282.333	0	0.0353	0	1	0
45.01	1	0	264.417	0	0.0328	0	1	0
42.01	0.965	0.035	250.659	328.350	0.0313	0.0305	0.4559	0.00669
40.01	0.951	0.048	241.224	329.035	0.0303	0.0299	0.3653	0.0135
32.01	0.933	0.067	201.153	332.097	0.0259	0.0278	0.3351	0.0157
29.01	0.934	0.066	184.949	333.563	0.0243	0.0271	0.4374	0.00839
24.01	0.941	0.059	156.227	336.639	0.0215	0.0261	0.3715	0.0131
17.01	0.957	0.043	112.159	342.656	0.0180	0.0248	0.4630	0.00601
9.01	0.979	0.021	58.072	350.375	0.0151	0.0227	0.4794	0.00442
5.01	0.989	0.011	31.412	350.449	0.0142	0.0203	0.4839	0.00397
1.51	0.997	0.003	9.215	338.948	0.0137	0.0152	0.4855	0.00381

Table 3: Accumulate Production Gas at Different Formation Pressure

Formation pressure (MPa)	50.98	50.17	40	32	24
Accumulate production gas (Gp)10^8m³	0	2	24.0	47.0	69.0
Accumulate production oil (Np)10^4m³	0	0	30.0	90.0	126

Assume:

$$Y = \rho_{\text{gsc}} G_{\text{p}} + \rho_{\text{osc}} N_{\text{p}}$$

$$X = B_{\text{gi}} \left\{ \rho_{\text{gi}} - [1 - \frac{\left(C_{\text{p}} + C_{\text{w}} S_{\text{wi}}\right)\Delta P}{1 - S_{\text{wi}}}] \cdot [\rho_{\text{g}}(1 - S_{\text{o}}) + \rho_{\text{o}} S_{\text{o}}] \right\}$$

The equation (13) can be converted to:

$$Y = GX \tag{17}$$

Then, Y will be proportional to X and the straight slope will be the dynamic geological reserves. Figure 3 can be drawn by substituted the physical property parameter and production datum into equation (17). Figure 3 shows that the dynamic geological reserves of M condensate gas reservoir were 157.52×10^8m³, which confirmed the mass balance equation in this paper.

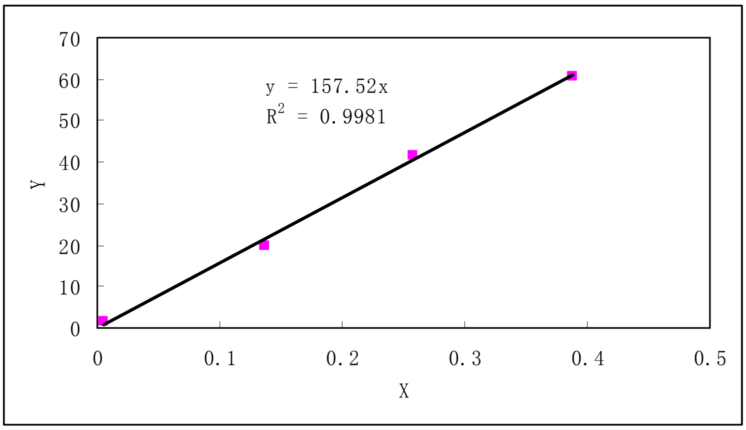

Fig.3: The relationship curve of X and Y for M condensate gas reservoir

CONCLUSION

The matter balance equation in this paper was based on the fundamental of mass conversation, the total mass of oil phase and gas phase remained same in the production period of condensate gas reservoir, which avoided consideration the composition and volume change of oil and gas caused by phase change.

No need to convert condensate oil to equivalent gas using empirical equation, which makes more reliable of this mass balance equation and matches better to the actual condition of condensate gas reservoir.

This material balance equation has been demonstrated by field case and the reserves calculated by it are reliable.

Nomenclature
Bgi= initial formation volume factor of gas, m^3/m^3
Bo= formation volume factor of condensate oil, m^3/m^3
Bw= formation volume factor of water, m^3/m^3
Bgdr= formation volume factor of injection gas, g/cm^3
ρgi= initial density of gas at formation condition, g/cm^3
ρgsc=density of gas at ground standard condition, g/cm^3
ρosc=density of condensate oil at ground standard condition, g/cm^3
ρg=density of gas at present formation condition, g/cm^3
ρo=density of condensate oil at present formation condition, g/cm^3
Gp=accumulate production of gas, 10^4m^3
Np=accumulate production of oil, 10^4m^3
G=original gas in place, 10^4m^3
Gip=accumulate injection of gas, 10^4m^3
So=saturation of retrograde condensed liquid in reservoir, decimal
Swi=irreducible water saturation, decimal
We= water influx in gas reservoir, m^3
Wp=accumulate production of water, m^3
Cp=compressibility coefficient of formation, MPa^{-1}
Cw=compressibility coefficient of water, MPa^{-1}

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