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A Novel Analytical Curve for Forecasting and Monitoring Gasflood Performance

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Abstract: With the increasing proportion of gas cap & artificial gas injection reservoirs, production performance monitoring and evaluation of gas-drive reservoir are becoming more and more important. However, there is no efficient method to forecast the production performance of gas-drive reservoir. In this paper, the analysis starts from the statistics of oil/gas relative permeability data of cores experiments. Based on fundamental principles of segregated flow and material balance, a new analytical curve of gasflood was developed to analyze the production performance. We applied the novel analytical curve to the production data from 23 gas-drive reservoirs at home and abroad and found a better power function relationship between dynamic reserves (N_d) and the slope (B) as foreseen by the analytical curve. It has been shown that the slope of the new curve represents dynamic reserves value; the smaller the slope value is, the more dynamic reserves are. Furthermore, by introducing the economic limit gas-oil ratio and control conditions which include initial and boundary conditions, a chart of dimensionless fractional flow of gas vs. recovery percent of OOIP is established to evaluate oilfield development rapidly and intuitively. Finally, many examples of application confirmed strongly that the new analytical curve used in gas-drive reservoirs is practical and effective, which broadens the scope of gas-drive oilfield research.

Keywords: Dynamic reserves evaluating, gasflood characteristic curve, gas-drive reservoir, recoverable oil reserves, relative permeability theory.

1. INTRODUCTION

Oil/gas-yielding rules in gasflood reservoirs become complicated when gas breakthrough occurs, which results in a lot of difficulties in the gasflood reservoir development. In order to improve the oil recovery during gasflood, it is crucial to afford an accurate estimation of reserves and future performance. In recent years, there have been many reports on developing semi-analytical and empirical model for estimating reserves and predicting performance, which are mainly applied in waterflood reservoirs [1-9]. However, for gas cap & artificial gas injection reservoirs, application of these methods will result in significant deviation or even do not completely apply to oilfield development.

At present, production performance forecasting of gasflood reservoir usually depends on numerical simulation method. However, the calculation accuracy of numerical simulation heavily relies on static and dynamic data quality and history match accuracy of reservoir, among which static data comes mainly from laboratory test. Generally, laboratory test is high cost in coring, low in efficiency, and difficult to track continuously, and the core can hardly reflect heterogeneity in reservoir scale.

Moreover, the history match accuracy is limited by depiction of geological conditions and experience of the engineers as well. Given this, widely developing reservoir engineering evaluation method is still the direction which needs to be worked on for a period of time in the future.

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Aimed at the difficulty of monitoring and evaluating the production performance of gasflood reservoir, the analysis starts from the statistics of oil/gas relative permeability data of cores experiments and a quantitative formula is also suggested between oil/gas relative permeability ratio and gas saturation in this paper. Based on fundamental principles of segregated flow and material balance, a new analytical curve of gasflood was developed to analyze the production performance and evaluate the development effect of fields with gasflood. And this method can also solve the following three problems in gasflood reservoirs: establishment of gasflood characteristic curve of research area; estimation of dynamic reserves; analysis of ultimate oil recovery and prediction of reservoir performance. Compared with numerical simulation and production decline model, oilfield application shows that the results are reliable, which expands the scope of research on reservoir engineering and has significance for evaluation of the development efficiency of gas drive reservoirs. The evaluation results will help to optimize the field gasflood operation. Furthermore, practical application shows that this technique is applicable at the individual-production-well level, pattern level, or for a reservoir as a whole.

2. DERIVATION OF GASFLOOD CHARACTERISTIC CURVE

2.1. Oil-Gas Relative Permeability Ratio and Gas Saturation

The most important theoretical basis for studying the gasflood characteristic curve is oil-gas relative permeability theory. Therefore, the key point of representing the percolation feature and regularity of gas-drive reservoir is to accu-

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rately describe the relevant relationship between oil-gas relative permeability ratio k_{rg}/k_{ro} and gas saturation S_g. Based on large amounts of data statistics and curve analysis, the authors put k_{rg}/k_{ro} placed on semi-logarithmic sheet of paper as a function of S_g, the relationships are shown as follows:

$$\lg(\frac{k_{rg}}{k_{ro}}) = \frac{S_g}{a + bS_g} + c \quad (1)$$

Equation (1) can represent the relationship between k_{rg}/k_{ro} and S_g in almost whole gas flow range. But for most of the production period of gas-drive reservoirs, the middle part of the curve is actually used in the analysis of reservoir performance. In this section, the analysis shows that the value of b in Eq. (1) is close to zero, which can be neglected to simplify the processing. Therefore, the equation (1) can be transformed as follows:

$$\frac{k_{rg}}{k_{ro}} = me^{nS_g} \quad (2)$$

Where, m=e$^{2.303c}$, n=2.303/a.

Combining with the core relative permeability data of three typical gas-cap sandstone reservoirs, the semi-logarithmic curves of k_{rg}/k_{ro} vs. S_g were drawn to validate the applicability of Eq.1 and the rationality of Eq.2 (Fig. **1**). Using Eq.1 and Eq.2 to fit different oil-gas relative permeability curves with different wettability, the results were shown in Fig. (**1a**-**1c**), from which it can be seen that characterization function of Eq.1 fits data well in interval of 10%-50% of S_g when characterization function of Eq.2 fits data well in interval of 10%-35% of S_g. Then based on Eq.2, a new gasflood characteristic curve was deduced to describe the relationships between k_{rg}/k_{ro} and S_g.

2.2. Material Balance Equation

Takeing a gas cap reservoir as example, we can treat water phase as irreducible water and assume that it won't occur in fluid flow when there is no water or a small amount of water rate in actual production period. Therefore, the gas saturation in the gas displacement process can be described as follows [10]:

$$S_g = 1 - S_{wi} - S_o \quad (3)$$

Where, the oil saturation is the ratio of the residual to total pore volume of reservoir. The material balance equation can be used to calculate oil saturation at any moment, as shown below:

$$S_o = \frac{(NE_v - N_p)B_o}{NE_v B_{oi} / (1 - S_{wi})} \quad (4)$$

When gas cap volume is much larger than that of oil rim, the formation pressure will be decreased slower because of the supplement to energy by the gas cap expansion. At this point, it can ignore the minute variation of gas density, gas solubility, as well as gas volume factor. Substituting Eq. (4) into Eq. (3), gives:

$$S_g = \frac{N_p}{NE_v}(1 - S_{wi}) \quad (5)$$

2.3. Derivation of the New Formula

Due to the complex fluid flow mechanism of gas drive reservoir, a number of simplifying assumptions must be made to keep the mathematical forms reasonably simple. The following assumptions, generally made, in most cases are appreciable: uniform pressure throughout the reservoir in both the gas and oil zones. This means gas and oil volume factors, gas and oil viscosities, and solution gas will be the same throughout the reservoir; Negligible capillary force and gravity forces; No water coning and negligible water production.

We can apply the Dray's law to describe oil and gas flow rate at reservoir conditions [11, 12]:

$$\frac{q_{ga}}{q_{oa}} = \frac{\mu_o}{\mu_g}\frac{k_{rg}}{k_{ro}} \quad (6)$$

It's important to note, however, that the q_{ga} and q_{oa} are the flow rate data at reservoir conditions, but the flow rate data at surface conditions are often used in actual work. Therefore, it needs to be converted as follows:

$$q_{oa} = q_o B_o\, ;\; q_{ga} = (q_g \text{-} q_o R_{si})B_g \quad (7)$$

Substituting Eq. (7) into Eq. (6) gives

$$\frac{(q_g \text{-} q_o R_{si})B_g}{q_o B_o} = \frac{\mu_o}{\mu_g}\frac{k_{rg}}{k_{ro}} \quad (8)$$

It can be seen that, when oil-gas viscosity ratio is a constant, the oil-gas flow rate ratio will mainly depend on oil-gas relative permeability ratio. Substituting Eq. (2) and Eq. (5) into Eq. (8), and taking transposition and derivation, gives:

$$\int_0^t q_g\, dt = \int_0^t (R_{si} + \frac{\mu_o B_o}{\mu_g B_g} me \frac{n(1 - S_{wi})N_p}{NE_v})q_o dt \quad (9)$$

For a specific oilfield, the cumulative oil or gas production can be expressed as follows:

$$G_p = \int_0^t q_g\, dt; N_p = \int_0^t q_0\, dt \quad (10)$$

Then substituting Eq. (10) into Eq. (9) gives

$$\lg(G_\text{p} - DN_\text{p} + C) = A + BN_\text{p} \quad (11)$$

Where,

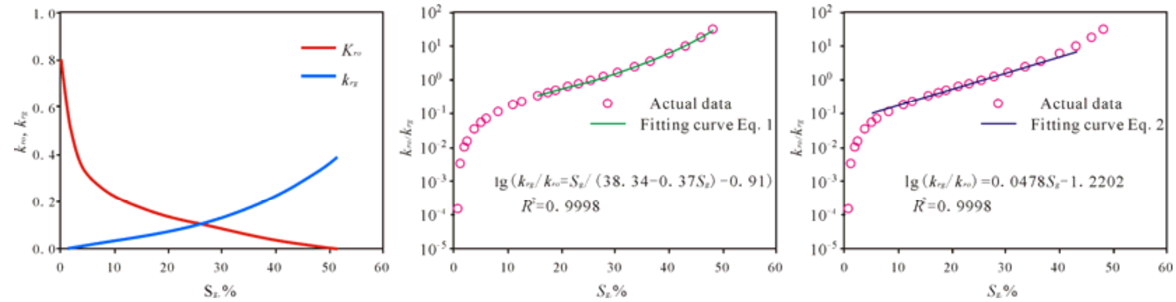
$$A = \lg(\frac{m\mu_o B_o NE_v}{n\mu_g B_g (1 - S_{wi})})\; ;\; B = \frac{n(1\text{-}S_{wi})}{2.303NE_v}\; ;$$

$$C = \frac{m\mu_o B_o NE_v}{n\mu_g B_g (1 - S_{wi})}\; ;\; D = R_{si} 。$$

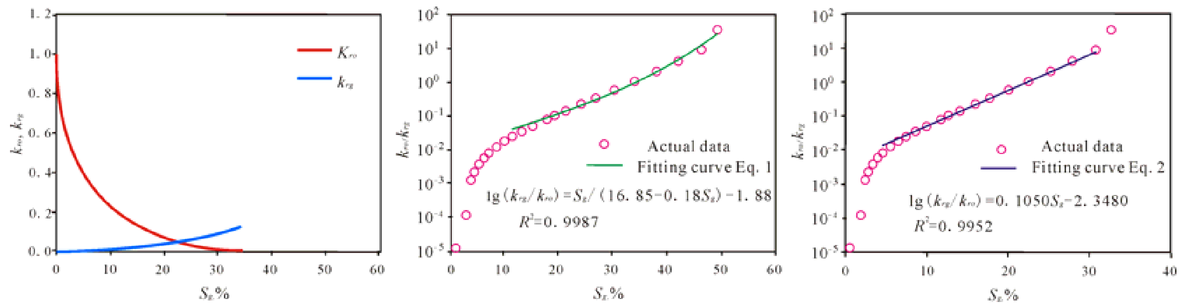
The Eq. (11) is new gasflood characteristic curve which can reflect the percolation feature of fluid in a porous medium for gas drive reservoirs.

Taking derivative of Eq. (11), we have

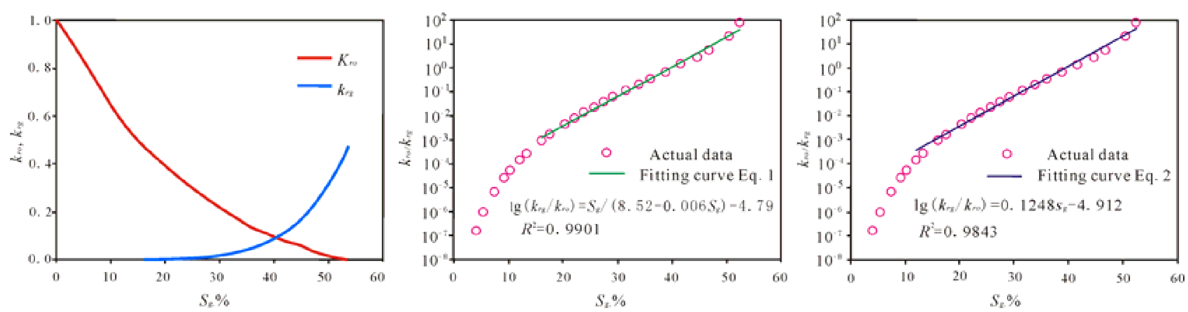
$$\frac{1}{G_\text{p} - DN_\text{p} + C}(q_g - Dq_o) = 2.303Bq_o \quad (12)$$



(a) Typical cores in Pucheng Oilfield (Water-wet)



(b) Typical cores in STZ Oilfield (Weak water-wet)



(c) Typical cores in Lamadian Oilfield (Oil-wet)

Fig. (1). Relationships between k_{rg}/k_{ro} and S_g as well as fitting curves of typical cores.

Substituting Eq. (12) into Eq. (11), we have

$$\lg(GOR - D) = A + \lg 2.303B + BN_p \tag{13}$$

By rearranging Eq. (13), one can obtain

$$N_p = \frac{\lg(GOR - D) - (A + \lg 2.303B)}{B} \tag{14}$$

Based on Eq. (14), we can solve the recovery percent of OOIP of reservoir at any time, which gives:

$$R = \frac{\lg(GOR - D) - (A + \lg 2.303B)}{BN} \tag{15}$$

Then we can introduce the economic limit gas-oil ratio GOR_{max} into Eq. (14) and Eq. (15) for forecasting recoverable oil reserves and the final recovery factor of gasflood reservoir, gives

$$N_R = \frac{\lg(GOR_{max} - D) - (A + \lg 2.303B)}{B} \tag{16}$$

$$E_R = \frac{\lg(GOR_{max} - D) - (A + \lg 2.303B)}{BN} \tag{17}$$

It's important to note that the economic limit gas-oil ratio is restricted by various factors, such as: reservoir types, development ways, driving energy, producing technology and cost of development, and so on. A number of variables synthetically determine the value of economic limit gas-oil ratio. Based on previous studies, if we do not take significant adjustment measures and change the way of development when the oilfield has already entered production decline stage, a semi-log relationships between gas-oil ratio and oil production can be expressed as [13, 14]:

$$\lg GOR = \alpha + \beta Q_o \tag{18}$$

Based on Eq. (18), we can approximately calculate the economic limit gas-oil ratio when given oilfield waste production.

3. REGULARITY ANALYSIS OF GASFLOOD CHARACTERISTIC CURVE

In order to provide insight into the physical significance and inherent law of the gasflood characteristic curve's coefficient, the authors have analyzed the production performance of 23 typical gas-cap reservoirs (most of them supplied by plenty of natural gas cap energy), and the data and relevant information were collected from published literature including the Mile six, Troll, STZ, Gao and JZ25-1S oilfield, and so on. The dynamic reserves of these reservoirs with a long history in producing are distributed from 95 to $3275\times10^4 m^3$. All of these lay a solid foundation for subsequent effectively analysis.

3.1. Slope of the New Curve and Dynamic Reservoirs

With examples of 23 typical oil fields, we have found that the inherent relation exists between the slope (B value) of the new curve and dynamic reserves of these oilfields. To make a diagram in linear coordinate about the value of dynamic reserves changes from the slope of the new curve, which presents a better power function relation, as shown in Fig. (**2**), giving:

$$N_d = 5.77B^{-0.98} \tag{19}$$

Eq. (19) can also be translated into another expression, which BN_d equals 5.2. Researches have shown that the slope of the new curve represents dynamic reserves value and the smaller the "B" value is, the more dynamic the reserves (N_d) are. Consequently, when we obtain the value of B by fitting production performance, we can also calculate the value of dynamic reserves of the reservoir which will also reflect the development efficiency.

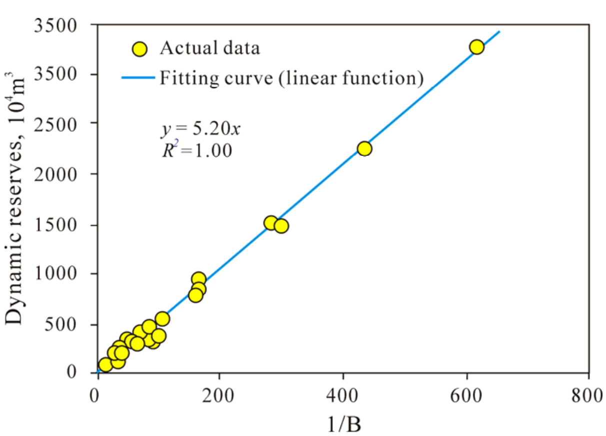


Fig. (2). Dynamic reserves versus the slope of the new curve.

3.2. Dimensionless Fractional Flow of Gas and Recovery Percent of OOIP

Relationships between gas-oil ratio and recovery percent of OOIP can be obtained on the bases of simultaneous equations (15), (17)

$$\lg(GOR - D) = 5.2(R - E_R) + \lg(GOR_{max} - D) \tag{20}$$

Then, introducing the correction coefficients a_1 and b_1 into Eq. (20), we have

$$\lg(GOR - D + b_1) = 5.2(R - E_R) + \lg(GOR_{max} - D) + a_1 \tag{21}$$

Initial conditions introduced: $GOR = R_{si} = D$, $R = R_i$, the following equations can be obtained from Eq. (21)

$$\lg b_1 = 5.2(R_i - E_R) + \lg(GOR_{max} - D) + a_1 \tag{22}$$

And also concerning the boundary condition: $GOR = GOR_{max}$, $R = E_R$, we can deduce expression about coefficient a_1, which can be expressed as

$$a_1 = \lg\frac{GOR_{max} - D + b_1}{GOR_{max} - D} \tag{23}$$

From Eq. (22), (23), we will also obtain the expression about coefficient b_1

$$b_1 = \frac{(GOR_{max} - D)10 \wedge (5.2(R_i - E_R)}{1 - 10 \wedge (5.2(R_i - E_R)} \tag{24}$$

Then substitute a_1 and b_1 into Eq. (21), the relation expression of gas-oil ratio and recovery percent of OOIP at any moment can be obtained. It's important to note that the parameter of R_i is the recovery percent of OOIP at period of gas- channeling free production.

To display the relationships between gas-oil ratio (GOR) and recovery percent of OOIP more visually, we can replace gas-oil ratio with dimensionless fractional flow of gas ($\overline{f_g}$), which can be expressed as follows:

$$f_g = \frac{10 \wedge (5.2(R - E_R) + \lg(GOR_{max} - D) + a_1 - b_1 + D)}{1 + 10 \wedge (5.2(R - E_R) + \lg(GOR_{max} - D) + a_1 - b_1 + D)} \tag{25}$$

$$\overline{f_g} = \frac{f_g - f_{gmin}}{f_{gmax} - f_{gmin}} \tag{26}$$

On the basis of above results, there are certain relationships between dimensionless fractional flow of gas ($\overline{f_g}$) and recovery percent of OOIP in gas drive reservoir, and which depends on the ultimate recovery of reservoir.

4. DEMONSTRATION CASES

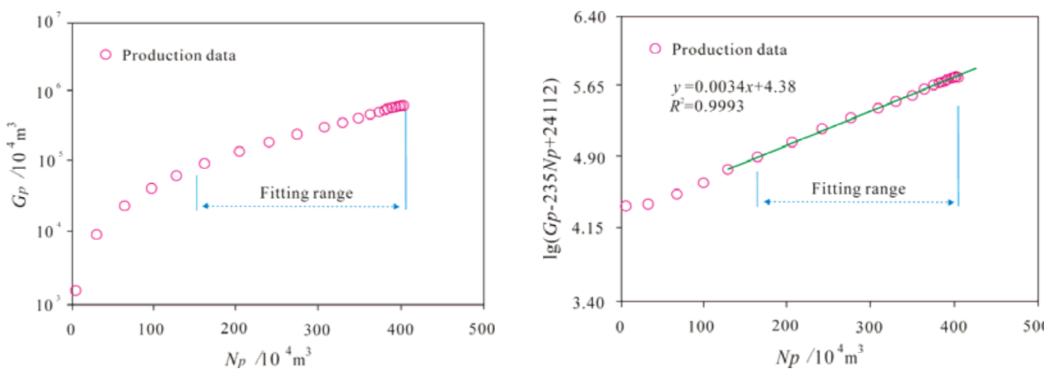
4.1. Case 1: S6 Reservoir

Field Case 1 (S6 reservoir) is for a typical large-scale gas cap reservoir at the STZ Oil field, China. The details of physical parameters of reservoir about study area are as shown in Table **1**. This field case study will further demonstrate the application of the new analytical method to forecast production performance. The reservoir started production in 1979 with the development of well pattern revised as 420m spacing square well pattern after 1981 to ensure stable production and make full use of nature gas cap energy. In the whole process, the oil is produced relying entirely on gas cap natural depletion. Based on this situation, the reservoir produced for 8 years at a steady state with an average recovery rate of 2.67%. Until 2000, the recovery degree has amounted to 25.9%.

The actual production data of S6 reservoir is taken from the open literature [15-17]. Based on actual production data of S6 reservoir, we can draw the relation curve of cumulative oil production vs. cumulative gas production and integrated function of cumulative oil & gas rate (Fig. **3a**, Fig. **3b**).

Table 1. Reservoir physical properties of typical gas cap reservoirs.

Name	Units	Parameter (S6 block)	Parameter (E block)	Name	Units	Parameter (S6 block)	Parameter (E block)
Reservoir type	-	Stratified structure	Stratified structure	Oil Density	g/cm^3	0.861	0.878
Sedimentary	-	River mouth bar	River mouth bar	Formation oil viscosity	mPa·s	0.5	0.71
Permeability	mD	331	325	Oil volume factors	-	1.658	1.216
Porosity	%	19	25	Gas Density	-	0.742	0.712
Initial oil saturation	%	65	60	Formation gas viscosity	mPa·s	0.031	0.019
Initial gas saturation	%	75	78	Gas volume factors	-	0.00478	0.00613
Irreducible water saturation	%	35	40	Initial pressure	MPa	24.7	16.5



(a) G_p versus N_p (b) N_p versus (G_p–DN_p+C)

Fig. (3). Gasflood characteristic curve of S6 block in STZ oilfield.

Then, the new analytical curve can be applied to match data in Fig. (**3b**) and obtain an expression as follows:

$$\lg (G_p\text{-}235N_p\text{+}24112) = 4.38\text{+}0.0034N_p \qquad (27)$$

Where, A = 4.38; B = 0.0034; C = 24112.

Plugging the parameter of B solved by Eq. (27) into Eq. (19), we can obtain the production reserves as 1529.41×10^{4}m^3. Compared to 1545.00×10^{4}m^3 by using the volume method, the relative error is only around 1.01%. These results also indicate that the reserves produced are high at the current development well pattern.

Next, we will make the actual production performance period from 2001 to 2009 to valid the applicability of the new analytical curve proposed in this paper. Based on the annual cumulative oil production data, we can apply Eq. (27) to forecast the annual cumulative gas production and compare with the actual data. Fig. (**4**) shows the contrast effect and we can see that the values of cumulative gas production were calculated using the new analytical curve which agrees well with actual data. Fig. (**5**) illustrates the relationships between annual oil production and gas/oil ratio in a decline period of study area. As can be seen from the scatter gram, there is a better semi-log relationships between both. Then, we can use the obtained equation to quantitatively calculate the oil field economic limit gas/oil ratio, which is 5623m^3/m^3. Plugging the parameter of B solved by Eq. (27) and the parameter of GOR_{max} into Eq. (16) we can get the economic recoverable reserves as 450.46×10^{4}m^3 as well as the recovery factor which is 29.15% and is coincident with the value of 29.75% forecasted by numerical simulation method after fine history matching. And now, the actual recovery degree of S6 reservoir has reached 28.20%. It has been fully illustrated that the potential of remaining recoverable oil reserves is limited.

In addition, we can make the actual production data fit with the chart of $\overline{f_g}$ vs. R, which can directly demonstrate the final development efficiency of study area. Fig. (**6**), for example, shows that the final economic recovery factor will be 29.5% if the oil field develops sequentially under the current well pattern.

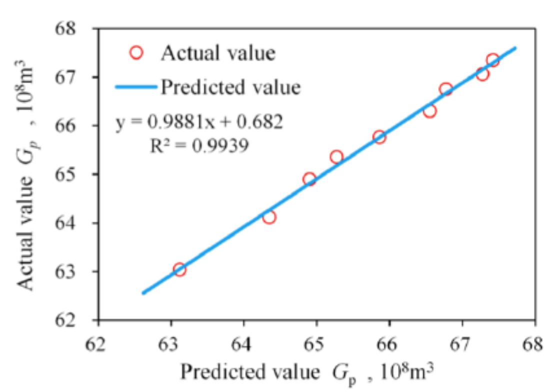


Fig. (4). Comparison between the predicted ratio value of G_p and actual value.

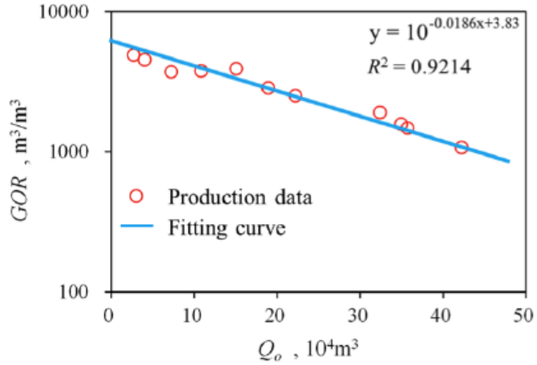


Fig. (5). Relation curves of gas-oil and annual oil rate.

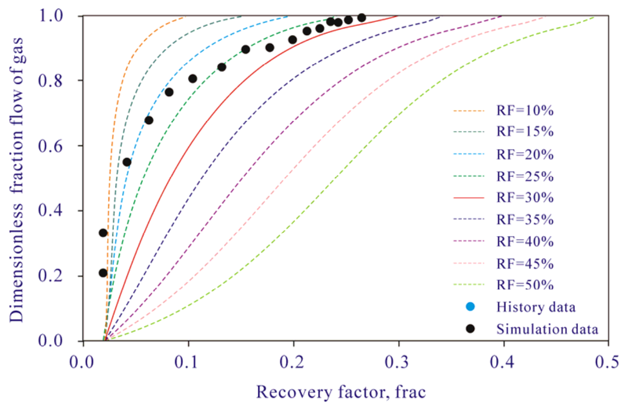


Fig. (6). Dimensionless fraction flow of gas versus recovery factor in S6 block.

4.2. Case 2: E Reservoir

Located in the north of the Liaodong Gulf in Bohai Bay, the JZ25-1S oilfield has a series of branchy anticline gas cap reservoirs controlled by structure developed in the Es 2 of the early Tertiary Shahejie formation in oilfield, with the most typical fault in block E. This block is a sandstone reservoir with a typical characteristic of big gas cap, edge and bottom water and narrow oil ring (gas cap index of 2.03, water multiples of 5 times, the width of the oil ring plane is less than 600m) [18, 19]. The detailed reservoir physical parameters are shown in Table **1**.

In Dec.2009, E reservoir has been formally put into production, which was developed by horizontal row well pattern under 750m well spacing. With an average recovery rate of 3.5%, the study area maintained a steady base level of production for 3 years, with reliance on gas cap natural energy expansion with the recovery percent of OOIP reaching 14.5%.

Based on actual production performance data of E reservoir (Table **1**), we can draw the relation curve of cumulative oil production vs. cumulative gas production or integrated function of cumulative oil & gas rate (Fig. **7a**, Fig. **7b**). Consequently, the new analytical curve can be applied to match data in Fig. (**7b**) and obtain an expression as follows:

$$\lg (G_p - 68N_p + 1970) = 3.29 + 0.0093N_p \quad (28)$$

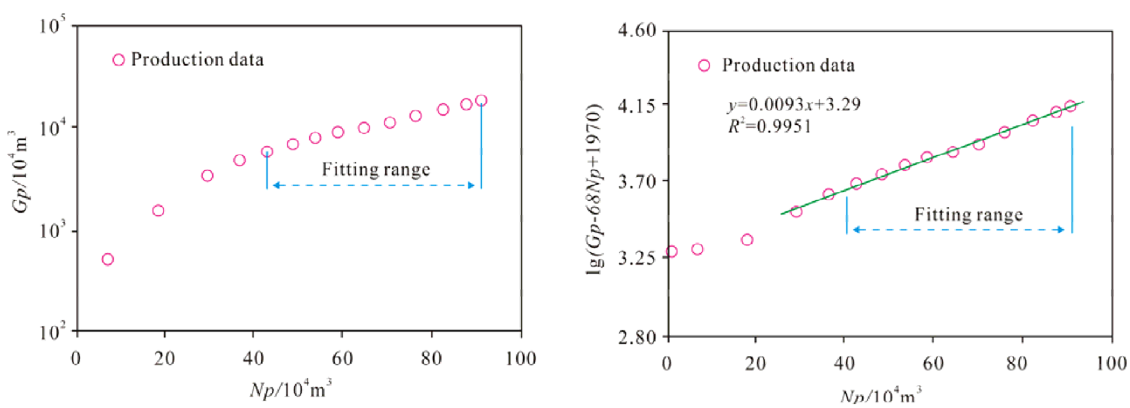
Where, $A = 3.29$; $B = 0.0093$; $C = 1970$.

After getting the value of GOR_{max}, plugging the above regression coefficients into Eq. (16) the recoverable oil reserves are $149.00\times10^4 m^3$ and the recovery factor is 23.8%. In order to validate calculation results through the new analytical curve, production decline model and numerical simulation technique are available to obtain the recoverable oil reserves (Fig. **8**). Here a brief introduction of production decline model is stated as follows: Production decline model was introduced in 1980 by Kepeituofu, a former Soviet scholar. The principle of this method is that there is a relationship between cumulative oil production and exploitation time in the period of production decline, gives:

$$N_p(\lambda + t) = \alpha + \beta(\lambda + t) \quad (29)$$

Where, the recoverable oil reserves calculated by production decline model is $147.23\times10^4 m^3$ and the recovery factor is 23.5%, as well as the recoverable oil reserves calculated by numerical simulation is $151.78\times10^4 m^3$ and the recovery factor is 24.3%. Forecasting results of two methods are combined with the new analytical curve. The comparison results fully demonstrate the effectiveness of the new analytical curve proposed by this paper.

Moreover, plugging the parameter of B solved by Eq. (28) into Eq. (19) the dynamic reserve is $559.14\times10^4 m^3$. It shows that parts of OOIP are not fully used under the current well pattern by comparing with $626.44\times10^4 m^3$ of volume method. To stabilize oilfield productivity and make the best



(a) G_p versus N_p (b) N_p versus ($G_p - DN_p + C$)

Fig. (7). Gasflood characteristic curve of E block in JZ25-1S oilfield.

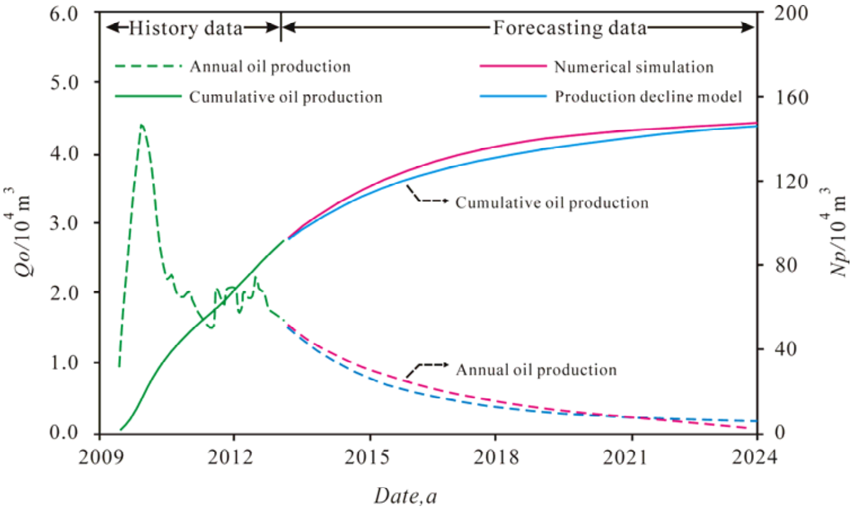
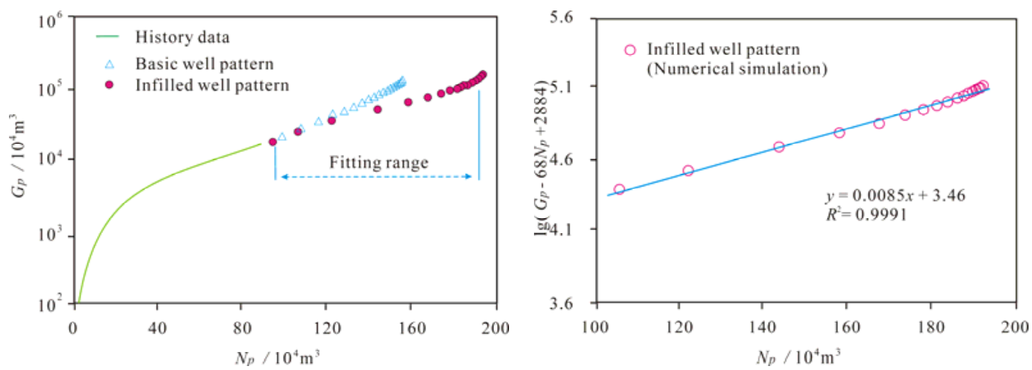


Fig. (8). Comparison between the applications of different methods.



(a) G_p versus N_p (b) N_p versus ($G_p - DN_p + C$)

Fig. (9). Gasflood characteristic curve of E block under different well patterns.

of gas cap energy, the numerical simulation model can be applied to analyze the feasibility of infilling on basic well pattern, and after infilling, the well spacing of oil rim is reduced from 700 to 350m. Using the method of gasflood characteristic curve derived, we could evaluate and forecast the development efficiency of oil-rim after infilling wells. As shown in Fig. (**9a**), the blue line and red line represent different production performance with different well patterns of E reservoir. Take the red line for example and draw a curve between cumulative oil production vs. integrated function of cumulative oil & gas rate (Fig. **9b**). Consequently, the new analytical curve can be applied to match data in Fig. (**9b**) and an expression can be obtained as follows:

$$\lg (G_p - 68N_p + 2884) = 3.46 + 0.0085N_p \quad (30)$$

By Equation (30), we got: A = 3.46; B = 0.0085; C = 2884. Put A, B and C into Equation (16), we obtained that the economic recoverable oil reserves is $191.00\times10^4 m^3$ and economic recovery factor is about 30.5% after infilling wells. Put B into Equation (19), we obtained that the dynamic reserves is $611.76\times10^4 m^3$ which is in accordance with $626.44\times10^4 m^3$ calculated by Volumetric method. These also indicated that infilling wells could improve the development efficiency by making use of residual oil between wells especially in the middle and later periods of the oilfield development. In order to compare the development efficiency before and after infilling wells more intuitively, we put production dynamic data into the chart of $\overline{f_g}$ vs. R (Fig. **10**). From Fig. (**10**), it is obtained that before infilling wells the Recovery factor is about 25%, and after infilling wells the recovery factor can reach about 32% with the curve trend gradually getting better. Examples of application confirmed strongly the new analytical curve used in gas drive reservoirs is practical and effective.

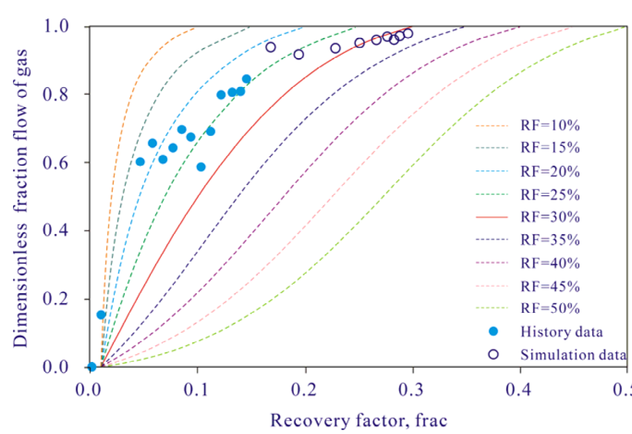


Fig. (10). Dimensionless fraction flow of gas versus recovery factor in E block.

CONCLUSION

Based on the work done in this paper, the following conclusions can be made:

1. On the basis of oil-gas seepage characteristic equation, material balance equation and Darcy's law, this paper proposed a new gasflood characteristic curve. After a variety of practice and statistical analysis, research indicates that the slope of the new curve has a strict physical interpretation.
2. Research shows that the slope of the new curve represents dynamic reserves value and the smaller the slope value is, the more dynamic reserves are.
3. Through theoretical analysis and proof, there are certain relationships between dimensionless fractional flow of gas and recovery percent of OOIP in gas-drive reservoirs, which depend on the ultimate recovery of reservoirs. Given the aforesaid research, the authors made the $\overline{f_g}$ vs. R relation graph.
4. Many applications show that the economic recoverable oil reserves and recovery factor can be calculated by the new method. Meanwhile, the new analytical curve was compared with the well-known production decline model and numerical simulation and the results calculated by three methods were consistent. More significantly, compared with numerical simulation, the new analytical curve is simple and practical. Besides that, the new analytical curve is able to predict the dynamic reserves of reservoirs, which is not the case for production of decline model.

NOMENCLATURE

$a, b, a_1, b_1, c, \alpha, \beta, m, n, C, D$ = Regression coefficient

A = The intercept of Eq.11

B = The slope of Eq.11

B_o = Oil formation volume factor

B_{oi} = Originally oil formation volume factor

B_g = Gas formation volume factor

E_v = Gas volume sweep efficiency, %

E_R = Recovery factor, *f*

f_g = Fraction flow of gas, *f*

f_{gmin} = The minimum of fractional flow of gas

f_{gmax} = The maximum of fractional flow of gas

$\overline{f_g}$ = Dimensionless fraction flow of gas, fraction

GOR = Free gas production gas/oil ratio, m^3/m^3

GOR_{max} = The economic limit gas/oil ratio, m^3/m^3

G_p = Cumulative gas production, $10^4 m^3$

k_{rg} = Gas relative permeability

k_{ro} = Oil relative permeability

N = Originally oil in-place, $10^4 m^3$

N_d = Dynamic reserves, $10^4 m^3$

N_p = Cumulative oil production, $10^4 m^3$

N_R = Recoverable oil reserves, $10^4 m^3$

Q_o = Oil production, $10^4 m^3/a$

Q_g = Gas production, $10^4 m^3/a$

R = Recovery percent, *f*

R_{si} = Solution gas/oil ratio, m^3/m^3

S_o = Oil saturation, *f*

S_g = Gas saturation, *f*

S_{wi} = Irreducible water saturation, *f*

μ_o = Oil viscosity at reservoir conditions, mPa·s

μ_g = Gas viscosity at reservoir conditions, mPa·s

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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