Research article

Quantitative calculation of GOR of complex oil-gas-water systems with logging data: A case study of the Yingdong Oil/Gas Field in the Qaidam Basin

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Abstract

In the Yingdong Oil/Gas Field of the Qaidam Basin, multiple suites of oil-gas-water systems overlie each other vertically, making it difficult to accurately identify oil layers from gas layers and calculate gas-oil ratio (GOR). Therefore, formation testing and production data, together with conventional logging, NMR and mud logging data were integrated to quantitatively calculate GOR. To tell oil layers from gas layers, conventional logging makes use of the excavation effect of compensated neutron log, NMR makes use of the different relaxation mechanisms of light oil and natural gas in large pores, while mud logging makes use of star chart of gas components established based on available charts and mathematical statistics. In terms of the quantitative calculation of GOR, the area ratio of the star chart of gas components was first used in GOR calculation. The study shows that: (1) conventional logging data has a modest performance in distinguishing oil layers from gas layers due to the impacts of formation pressure, hydrogen index (HI), shale content, borehole conditions and invasion of drilling mud; (2) NMR is quite effective in telling oil layers from gas layers, but cannot be widely used due to its high cost; (3) by contrast, the star chart of gas components is the most effective in differentiating oil layers from gas layers; and (4) the GOR calculated by using the area ratio of star chart has been verified by various data such as formation testing data, production data and liquid production profile.

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1. Introduction

Located in the Yingxiongling region of the western Qaidam Basin, the Yingdong Oil/Gas Field ranks the second among the four integral oil and gas fields discovered there in recent years, the production of which all reach hundred million tons. It features long hydrocarbon-bearing intervals, large cumulative thickness of oil and gas layers [1] and relatively thin single layers. Oil and gas layers are difficult to identify due to the well-developed faults in the Yingdong Oil/Gas Field [2] and the vertical stacking of multiple oil-gas-water systems. Gas layers are perforated as oil layers now and then, which greatly increases the pressure of surface oil lines. Meanwhile, oil/gas reservoir pressure decreases rapidly due to the production of high GOR reservoirs. The above-mentioned factors are not good for the development of these reservoirs. Therefore, it is urgent to address the issue of oil and gas layer identification and quantitative GOR calculation for the Yingdong Oil/Gas Field.

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2. Reservoir overview

2.1. Reservoir lithology and petrophysical properties

The reservoirs are medium in compositional maturity, medium-high in textural maturity, fine in grain size, low in matrix content, medium-low in cement content, and weak in diagenesis. Reservoir rock, relatively stable in type, is lithic feldspar sandstone. Fine in grain size, the sandstone is mainly medium sandstone-siltstone, with an average cement (mainly calcite) content of 7%. The reservoir pores are well-developed and quite even in distribution with fine connectivity. The reservoir space is composed of intergranular pores, followed by dissolution pores and a small amount of fissures, accounting for 81.7%, 15.5% and 2.8% respectively. The reservoirs have a porosity of 10.0%−23.0%, 20.4% on average, and a permeability of 0.1−500 mD, 124.9 mD on average.

2.2. Reservoir temperature and pressure

The reservoirs have a geothermal gradient of 3.08 °C/(100 m), representing normal temperature system. According to the field measured 26 data points of temperature versus depth, the fitted formula of temperature and depth is written as:

\[ T = 10.428 + 0.0308D \ (R = 0.9550) \]  

where \( T \) is formation temperature, °C; \( D \) is formation depth, m.

The formation pressure gradient is 1.07 MPa/(100 m), representing normal pressure system. According to the field measured 26 data points of pressure versus altitude, the fitted formula of pressure and altitude is written as:

\[ p = 31.479 + 0.0107H \ (R = 0.9849) \]  

where \( p \) is formation pressure, MPa; \( H \) is altitude of measured point, m.

2.3. Reservoir oil and gas properties

The surface crude is identified as light medium-viscosity oil, with an average density of 0.842 t/m³, average viscosity of 9.4 mPa s, average paraffin content of 14.0%, average gasoline content of 10.1%, average kerosene & diesel content of 28.3%, average setting point of 30.0 °C, average wax precipitation point of 45.0 °C, and average initial boiling point of 144.0 °C. The oil PVT test demonstrates that the DGOR (dissolved gas-oil ratio) is 20.7−99.0 m³/m³, 74.0 m³/m³ on average under original formation pressure.

The gas has a relative density of 0.638, average methane content of 88.05%, average ethane content of 3.78%, average propane content of 1.63%, average heavy hydrocarbon content of 1.48%, average nitrogen content of 4.65%, and average carbon dioxide content of 0.41%. The gas PVT test shows that the gas has a volume factor of 0.007 08−0.011 93, density of 0.061−0.101 t/m³, viscosity of 0.013 7−0.015 6 mPa s, and deviation factor of 0.837 9−0.870 1 (0.854 0 on average) under original formation pressure, representing dry gas.

3. Qualitative identification of oil and gas layers

3.1. Differentiation of oil and gas layers with conventional logging

Resistivity [3] and excavation effect of compensated neutron logging [4,5] are often used to identify oil and gas layers in conventional logging.

However, the resistivity of oil and gas layers principally reflects reservoir petrophysical properties rather than oil or gas properties when the oil and gas layers have similar water saturation. In addition, the invasion depth of fresh water drilling fluid varies significantly due to relative high formation water salinity in the Yingdong Oil/Gas Field and relatively large petrophysical difference of different reservoirs. Resistivity mainly reflects reservoir petrophysical properties and drilling fluid invasion under comparative water saturation [6], but doesn't show obvious differences between oil layers and gas layers, so resistivity is not suitable for the Yingdong Oil/Gas Field.

The excavation effect of compensated neutron logging method is based on the assumption that the compensated neutron logging porosity will decrease and the apparent porosity of acoustic and density loggings will increase in gas layers, so there will be some differences between the porosity measured by compensated neutron logging and the apparent porosity measured by acoustic and density loggings in gas layers. However, different gas layers are different in formation...
pressure, hydrogen index and density [7]; meanwhile, the three-porosity curves are also influenced by shale content, lithic component content and other factors, thus covering gas responses to some extent. In addition, the frequent borehole enlargement in sandstone and mudstone formation would lower the quality of the measured three-porosity data. Fig. 1 is an identification crossplot for oil and gas layers with excavation effect of compensated neutron logging. It can tell oil layers from gas layers in regular borehole intervals with qualified three-porosity curves, but cannot identify oil-gas layers.

3.2. Oil and gas layer identification with NMR

NMR has unique functions in describing reservoir pore structures [8] and fluid properties [9, 10]. The transverse relaxation time \( T_2 \) measured by NMR can be expressed as [11]:

\[
\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{D(\gamma GT_E)^3}{12} + \frac{\rho_2 S}{V}
\]

(3)

where, \( T_{2B} \) is relaxation time of fluid volume, ms; \( D \) is diffusion coefficient, \( \mu^2/\text{ms} \); \( G \) is magnetic field gradient, Gs/cm; \( T_E \) is echo spacing, ms; \( S \) is pore surface area, \( \text{cm}^2 \); \( V \) is pore volume, \( \text{cm}^3 \); \( \rho_2 \) is transverse surface relaxation strength of rock, \( \mu\text{m}/\text{ms} \).

\( T_2 \) relaxation time would be fairly long due to the volume relaxation of light oil in large pores, which is the so-called tailing phenomenon. Natural gas has no volume relaxation. Since it has a large diffusion coefficient, its \( T_2 \) relaxation time decreases, which is called the forward shift of \( T_2 \) spectrum [12].

Fig. 2 is the oil and gas layers identification plot of Well X1 with NMR. Obvious \( T_2 \) spectrum tailing phenomenon can be seen in M and N layers, some signals are more than 1000 ms, so the two layers are identified as oil layers. The \( T_2 \) relaxation time of Y and Z layers is basically below 1000 ms, so the two layers are identified as gas layers. NMR can identify oil layers from gas layers clearly, however, NMR is only conducted in key intervals of a small portion of wells due to high cost and long logging time, so it cannot be widely applied.

3.3. Oil and gas layer identification with mud logging

Mud logging is a method to find out underground reservoirs by measuring combustible gas content in mud. The collected gas is fractionated, identified and measured by chromatographic column in chromatographic mud logging technology, and the content of \( C_1-C_5 \) can be continuously recorded respectively [13]. Currently, mud logging is mainly applied in identifying oil and gas reservoirs, and the corresponding interpretation methods include chart boards and mathematical statistics. The commonly used chart board methods include Pixler Chart [14], hydrocarbon triangular diagram method [15], hydrocarbon proportion chart board, humidity chart board [13], etc. These chart board methods, using few parameters (only \( C_1-C_4 \)) but without distinguishing n-paraffins and iso-paraffins, don’t make full use of mud logging data.

Conventional mathematical statistic methods include R-factor analysis [16], fuzzy pattern recognition, BP neural network [17], Fisher Linear Discriminant analysis, Mahalanobis distance discriminant analysis [18], and Euclidean distance analysis [19], etc. The common advantage of these mathematical statistic methods is drawing on more data, however, these methods often require a certain amount of samples, and are complex and inconvenient in application. On
the whole, both chart boards and mathematical statistics are mainly applied to find oil and gas layers in current mud logging [20], focusing on differentiation of oil and gas layers from water layers rather than differentiation of oil layers from gas layers.

The star chart board of gas components is put forward to identify oil layers from gas layers based on comprehensive comparison of different methods and tests in the Yingdong Oil/Gas Field. Seven ratios, i.e. C1/C2, C1/C3, C2/C3, C2/iC4, C3/iC4, iC4/nC4 and iC5/nC5, are used in the star chart board of gas components, which, making full use of mud logging data, can accurately identify oil layers, oil-gas layers and gas layers in the Yingdong Oil/Gas Field. Formation testing and production data have confirmed the coincidence rate of star chart board hits over 90% (Fig. 3).

4. Quantitative calculation of GOR

There are fewer researches on quantitative calculation of GOR. Gao Chuqiao et al. [21] took condensate gas as a component of formation volume model to establish logging response equation, and established over-determined equation set based on multiple logging curves to get optimal solution of GOR, but he pointed out this method was prone to the effect of mud invasion and needs correcting in application. Li Fangming et al. [22] established the qualitative relationship between “excavation effect of compensated neutron log” and GOR, but the study objects are oil reservoirs in which all produced gas is dissolved gas, therefore, the above-mentioned methods are not applicable to the Yingdong Oil/Gas Field.

Since there are some limitations in telling oil layers from gas layers with logging in the Yingdong Oil/Gas Field, mud logging data which is effective in distinguishing oil layers from gas layers was adopted to calculate GOR by the authors. As is shown in Fig. 4, the total area encircled by sample data points in the star chart board of gas components can be divided into two parts: the first part is the quadrangle encircled by C1/C2, C1/C3, C2/C3 and coordinate original point, its area \( S_a \) is related to the content of light hydrocarbon content; the second part is the heptagon encircled by C2/C3, C2/iC4, C3/iC4, iC4/nC4, iC5/nC5, C1/C2 and coordinate original point, and its area \( S_b \) is related to heavy hydrocarbon content. In general, \( S_a > S_b \). For gas layers, \( S_a > S_b \), \( S_b \) is very small. For oil layers, \( S_b \) is relatively large. The \( S_a \) area of oil-gas layers falls in between the former two.

After the division of the gas components on star chart, the area ratio \( S_a/S_b \) can be calculated with formula (2). Then, a mathematical fitting is performed to establish the relationship between the area ratio and GOR measured by oil and gas test (Fig. 5). They are in power function relationship shown as Formula (4). The larger the area ratio \( S_a/S_b \), the higher the GOR will be.

\[
S_a = \left( \frac{C_1 C_1 C_2 + C_1 C_2}{C_2 C_3 + C_3 C_1} \right) / \left( C_2 C_2 C_3 + C_3 C_1 + C_3 iC_4 + iC_4 iC_4 + iC_4 nC_4 + iC_5 nC_5 \right) \\
S_b = \left( C_1 C_1 C_2 + C_1 C_2 \right) / \left( C_2 C_3 + C_3 C_1 + C_3 iC_4 + iC_4 iC_4 + iC_4 nC_4 + iC_5 nC_5 \right) \\
\]

where \( S_a \) is the quadrangle area related to light hydrocarbon content, dimensionless; \( S_b \) is the heptagon area related to heavy hydrocarbon content, dimensionless. C1 is methane content; C2 is ethane content; C3 is propane content; iC4 is iso-paraffin content; nC4 is n-paraffin content; iC5 is iso-pentane content; nC5 is n-pentane content.

\[
GOR = 3.0445 \left( \frac{S_a}{S_b} \right)^{4.3005} \tag{5}
\]

where, \( GOR \) is gas-oil ratio, \( \text{m}^3/\text{m}^3 \).

Fig. 6 is an example of GOR quantitative calculation with mud logging data of Well X2 in the Yingdong Oil/Gas Field. In the interval of 1450–1485 m, the “excavation effect” of conventional logging cannot effectively identify oil layers.
from gas layers, because oil layers and gas layers here have similar “images” on density and compensated neutron logs. When put into production, six layers (A–F) in Well X2 were perforated together, daily flowing production with 5 mm choke was 9.74 m$^3$/d oil, 9602 m$^3$/d gas and 0.13 m$^3$/d water on average. By using the star board of gas components, Layer A, Layer B and Layer C were identified as oil and oil-gas layers with the corresponding GOR of 36 m$^3$/m$^3$, 2000 m$^3$/m$^3$ and 180 m$^3$/m$^3$ respectively; Layer D, Layer E and Layer F were identified as gas layers, with the corresponding GOR of 48 000 m$^3$/m$^3$, 27 000 m$^3$/m$^3$ and 37 000 m$^3$/m$^3$ respectively. The identification results are consistent with that of ultrasonic three-phase production profile test.

5. Conclusions

(1) Conventional well logging cannot accurately identify oil and gas layers due to the influence of formation pressure, hydrogen index, shale content, borehole conditions, mud invasion and other factors. NMR is effective in

![Fig. 5. The relationship between the star chart of gas component area ratio and GOR.](image)

![Fig. 6. An example of GOR quantitative calculation with mud logging of Well X2.](image)
distinguishing oil and gas layers but cannot be widely applied due to high cost. The star chart of gas components is the best choice to identify oil and gas layers.

2. Area $S_a$ in the star chart of gas components is related to light hydrocarbon content, the area $S_b$ is related to heavy hydrocarbon components, and there is a good correlation between the area ratio $S_a/S_b$ and GOR, the bigger the area ratio $S_a/S_b$, the higher the GOR will be.

3. Actual field data demonstrates that the oil and gas layers identification and GOR quantitative calculation based on mud logging are suitable for the Yingdong Oil/Gas Field.

References