Application of Thermal Neutron Imaging System in Oil & Gas Field development

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Abstract: The correct identification of oil and gas reservoirs is very important in oil and gas field production. To solve the problem of oil and gas reservoir evaluation in low salinity and low porosity reservoirs, thermal neutron imaging system (TNIS) is introduced. The advantage of TNIS is that it can record a large number of formation information through multiple detectors to obtain imaging documents, allowing intuitive quantitative analysis of formation, and calculate oil and gas saturation through thermal neutron capture cross section, attenuation spectrum and capture spectrum, so as to obtain oil/gas/water distribution near wellbore. In the processing, interpretation and evaluation of thermal neutron imaging logging data, the interpretation model, parameters and criteria are established according to the geological characteristics of lithology and formation water salinity of the target block, which improves the interpretation coincidence rate. Field application shows that thermal neutron imaging logging has achieved sound effects in identifying watered-out zone, potential zone, gas reservoir and residual oil distribution monitoring.

1. INTRODUCTION

Hydrocarbon reservoirs identification is a crucial issue in oil and gas field production. Many maturing oilfields have entered the stage of "high water cut and high recovery". It is more and more difficult to stabilize oil productivity and control water production. In terms of economic development, it is a practical method to find remaining oil, that is, to identify potential layers. Logging is an important approach to identify oil and gas reservoirs, including conventional resistivity logging, fluid production profile testing, pipe string water prospecting and other methods, which play an important role, while with some problems. It is difficult to determine formation water resistivity, an important parameter of conventional resistivity log interpretation, because the resistivity of mixed fluid varies greatly in the middle and later stages of reservoir development. In multi-layer production, poor physical properties and low pressure layers will be inhibited, and the test results of fluid production profile sometimes can not reflect the actual situation. Pipe-string water-finding method has no advantages in construction period, cost, accuracy of test results.

Saturation logging is an important method for hydrocarbon reservoir identification. Many saturation logging tools, such as C/O tester[1], neutron lifetime logging tool[2], reservoir performance monitoring tool (RPM)[3], reservoir monitoring tool (RMT)[4], reservoir saturation logging tool (RST)[5], pulse neutron attenuation spectrum logging (PND)[6] and Pulse neutron-neutron(PNN) logging[7][8] have obtained some effects. However, in some reservoirs with lower salinity and smaller porosity, the above methods can not meet the needs of residual oil monitoring. Thermal Neutron Imaging System(TNIS) logging is introduced for this purpose. TNIS can directly distinguish
oil/gas/water distribution near wellbore and calculate water saturation by thermal neutron capture cross section, attenuation spectrum and capture spectrum. In the processing, interpretation and evaluation of TNIS logging data, the interpretation model, parameters and criteria are established according to the geological characteristics such as lithology and salinity of formation water in the target block, which improves the interpretation coincidence rate. Field application shows that TNIS logging has achieved good results in identifying potential layer, flooded layer and residual oil distribution monitoring.

2. INTRODUCTION OF TNIS

2.1 Measurement Principle
TNIS is a Σ type saturation measuring instrument based on pulsed neutron generator. Fast neutrons are emitted to the formation by a neutron generator. After a series of inelastic collisions and elastic collisions, when the neutron energy and the atoms constituting the formation are in thermal equilibrium, the neutrons will no longer decelerate, which are called thermal neutrons. The nuclear reaction with the formation is mainly a capture reaction. TNIS detects the thermal neutrons which have not been captured by the formation after the formation deceleration. The thermal neutron counting rate depletion in 2700us time after the fast neutron beam is emitted from the fast neutron beam for 15us is recorded by high precision detectors with long and short source spacing. Each detector divides its time spectrum into 180 time channels, and generates thermal neutron attenuation spectrum and capture spectrum according to the thermal neutron counts recorded by each detector. Neutron capture cross-section(Σ) can directly distinguish oil/gas/water distribution near wellbore, and calculate oil saturation, reservoir porosity, shale content and main mineral content through Σ value.

Hydrogen is the most important element in the process of fast neutron deceleration. TNIS logging can calculate the formation hydrogen index by changing the neutron counting rate of detectors with different source spacing, and then calculate the formation porosity. In the process of thermal neutron collision with elements in formation, the common nuclear reaction is capture reaction. The capture ability of different elements to thermal neutron varies greatly. Boron, lithium and chlorine are strong capture agents for thermal neutron, while hydrogen, carbon, oxygen, calcium, silicon and other elements are weak capture agents. Boron and lithium elements generally exist in mud, while chlorine elements generally exist in formation water. According to the capture cross-section, chlorine-bearing water, salt rock as well as oil and gas reservoirs can be distinguished. Mudstone, shale and sandstone can also be distinguished based on the content of boron and lithium.

The advantage of TNIS is that it can record a large amount of formation information through multiple detectors and form imaging files, which can analyze formation. TNIS system has many advantages thanks to the unique design. It can adapt to different salinity of formation water and get accurate formation saturation parameters in low formation porosity environment. The main indicators are shown in Table 1.

| Instrument Diameter | Instrument Length | Instrument Temperature | Instrument Pressure | Neutron Yield | Measuring Speed |
|---------------------|-------------------|------------------------|---------------------|---------------|----------------|
| 43mm                | 6.3m              | 175°C                  | 103MPa              | 2.0×10^8 n/s  | 2m/min         |

2.2 Main Characteristics
TNIS detects thermal neutrons which have not been captured, eliminating the influence of background value of gamma detection method, while maintaining relatively high counting rate in low salinity and low porosity formations. Unique data processing method can eliminate the influence of wellbore and intrusion zone as far as possible, and then truly evaluate the current hydrocarbon saturation of reservoir. The unique thermal neutron capture imaging technology makes the interpretation results more intuitive. The requirement for wellbore conditions is not much, and it is unnecessary to wash
wells and stop production operation to start and exit tubing.

3. DATA INTERPRETATION

Under the circumstance that other conditions are same, because the formation water has a higher capture cross-section, the more formation water is contained in the pore, the larger the measurement value of capture cross-section is. Therefore, the water saturation can be calculated by using the capture cross-section data. In the meantime, by referring to the time-track thermal neutron, Sigma BH ring imaging, thermal neutron capture spectrum and attenuation spectrum, TNIS can evaluate the remaining oil saturation and reserve, and determine the reservoir mobilization. The above is the basic principle of TNIS data interpretation.

3.1 Interpretation Model

TNIS completes the measurement under the condition of cased wells, and the measurement section contains sandstone and mudstone. Comprehensive interpretation of TNIS logging data utilizes some open hole logging data, such as shale content calculated by GR curve, porosity calculated by AC, oil saturation calculated by deep resistivity curve, and the corresponding interpretation and calculation model is no longer described.

TNIS log calculates oil saturation based on capture cross-section curve. The interpretation model for oil-bearing shaly rocks is as follows:

\[
\Sigma = (1 - \phi - V_{sh}) \sum_{ma} + V_{sh} \sum_{sh} + \phi S_w \sum_w + \phi (1 - S_w) \sum_h
\]

(1)

\[
S_w = \frac{(\Sigma - \sum_{ma}) + (\sum_{ma} - \sum_{sh}) V_{sh} + \phi (\Sigma_{ma} - \sum_{h})}{\phi (\sum_w - \sum_{sh})}
\]

(2)

The sensitivity analysis of parameters shows that \( \Sigma_{sh}, \Sigma_{u} \) and \( V_{sh} \) in the volume model are more sensitive to the calculation of water saturation. The volume model is improved by adding two regional characteristic coefficients \( K_1 \) and \( K_2 \) to \( \Sigma_{sh}, \Sigma_{w} \) and \( V_{sh} \) terms.

\[
\Sigma = (1 - V_{sh} - \phi) \sum_{ma} + K_1 V_{sh} \sum_{sh} + K_2 S_w \sum_w + (1 - S_w) \sum_h
\]

(3)

\[
S_w = \frac{(\Sigma - \sum_{ma}) - \phi (\Sigma_h - \sum_{ma}) - V_{sh} (K_1 \Sigma_{sh} - \sum_{ma})}{\phi (K_2 \sum_w - \sum_{sh})}
\]

(4)

Two water layers are chosen to calculate \( K_1 \) and \( K_2 \)

\[
K_1 = \frac{\sum_1 - \phi_1 \sum_{ma} + \sum_{ma} [\phi_1 (1 - V_{sh2} - \phi_2) - \phi_2 (1 - V_{sh1} - \phi_1)]}{\sum_{sh} (V_{sh1} \phi_2 - V_{sh2} \phi_1)}
\]

(5)

\[
K_2 = \frac{\sum_{sh} (V_{sh2} - \phi_2) - \sum_{sh} (1 - \phi_2)(1 - V_{sh1})}{\sum_{sh} (V_{sh2} - \phi_1)}
\]

(6)

In equation (1), (2), (3), (4), (5) and (6), \( \Phi \) is formation porosity, decimal; \( S_w \) is formation water saturation, decimal; \( \Sigma_{ma} \) is rock skeleton capture cross-section, c.u.; \( \Sigma_{sh} \) is formation water capture cross-section, c.u.; and \( V_{sh} \) is mud content. Decimal; \( \Sigma_{sh} \) is mudstone capture cross-section, c.u.
3.2 parameter determination

3.2.1 Determination of formation water capture section \( \Sigma_w \)

The cross-section value of formation water capture varies with the composition and salinity of salt ions. For pure formation water, its value is 22c.u. When there are strong neutron absorbers such as Cl, B and Li in formation water, the thermal neutron capture cross sections differ greatly from those of pure water. At room temperature, the thermal neutron capture cross sections of Cl, B and Li per microgram are 540c.u, 416c.u and 60.9c.u, respectively. For the value of water containing these ions, the ion is first converted to the equivalent concentration of NaCl thermal neutron capture cross section, and then the value of formation water is calculated according to the relationship between the equivalent NaCl content and the value of water. The equivalent coefficients of common materials are shown in Table 2.

| material | NaCl | Be | Mg | Ca | S | I | Li | Cd | Br | HCO_3^- |
|----------|------|----|----|----|---|---|----|----|----|---------|
| coefficient |     | 1  | 0.004 | 1.65 | 0.05 | 0.02 | 0.028 | 0.094 | 17.3 | 495 | 23.7 | 0.14 | 0.01 |

After calculating the equivalent sodium chloride concentration, the cross-section value of formation water capture is mainly a function of salinity. The relationship between the cross-section value of formation water capture and salinity of formation water needs to be fitted according to the actual data of different blocks.

3.2.2 Determination of mudstone capture cross-section \( \Sigma_{sh} \)

In practice, the mudstone capture cross-section \( \Sigma_{sh} \) is determined mainly according to the actual situation of the well location. The measured curve value \( \Sigma \) can be read from the mudstone section of the pure thick layer measured by the well, and the mudstone section which is close to the layer or whose distribution is relatively stable in other blocks of the study location can be read. The mudstone capture cross-section of the section can be obtained by statistical analysis of the capture cross section.

In practical application, there is another more accurate method for calculating the mud capture cross-section value. The mud capture cross-section value is determined by using the method of oil-water line equality in mudstone section. The details are as follows:

The oil line is defined as 100% oil in the pore, and the oil line is defined as:

\[
\Sigma_o = (1 - V_{sh} - \phi) \Sigma_{ma} + V_{sh} \Sigma_{sh} + \phi \Sigma_{li}
\]  

(7)

The water line is defined as 100% water in the pore, and the water line is defined as:

\[
\Sigma_w = (1 - V_{sh} - \phi) \Sigma_{ma} + V_{sh} \Sigma_{sh} + \phi \Sigma_{li}
\]  

(8)

By adjusting \( \Sigma_{sh} \), the oil line \( \Sigma_o \), water line \( \Sigma_w \) and logging curve \( \Sigma \) basically coincide in mudstone section, thus obtaining the mudstone capture cross section value.

4. FIELD APPLICATION

4.1 Identification of flooded and potential layers

Many old oilfields have entered the middle and later stages of development. Because of long-term water flooding development, the fluid production situation of various layers underground has changed greatly. Many layers have been flooded. Because the lithology and physical properties of each layer are quite different, the water flooding degree of each layer is also very different. Because of the multi-layer combined mining, the production of fluid in the poor physical properties layer will be inhibited, so it is necessary to determine which layers have production potential. Well A produces 3.5 cubic meters of fluid and 0.4 tons of oil per day with 87.2% water cut before testing. TNIS logging was carried out on February, 2017. Among them, the natural gamma value of unit No.26 is extremely high after casing, and the well temperature is also unbelievably high, which has the characteristics of
high water-cut fluid supply. TNIS has lower edge amplitude and darker color, showing higher water content. Comprehensive judgment is the main effluent interval. Remaining oil is relatively enriched at the top of unit No. 23. Quantitative interpretation of remaining oil saturation is 43%, which is interpreted as medium flooded zone. Later, on February 14, other high water-flooded zones were blocked and unit No. 23 was recovered alone. After stable production, 5.6 cubic meters of fluid and 2.2 tons of oil per day were produced with 60.7% water cut. Oil production per day increased by 1.8 tons and water cut decreased by 26.5%. Practice has proved that the interpretation conclusion of TNIS is correct. TNIS interpretation results are shown in Figure 1.

Figure 1  TNIS logging interpretation result diagram of well A

4.2 Re-examination of old wells and determination of remaining oil
It is important to evaluate old wells and re-recognize unused reservoirs. Well B is located in Block L in Bohai Bay Basin, with a total salinity of 12,000 ppm and an estimated porosity of 24%. Prior to TNIS test, Well B normally produced 20t of liquid per day with 100% water content. Unit No.31 was interpreted as an oil-water layer by conventional logging interpretation. After TNIS test, the middle 2m (1526.5-1528.5m) of unit No.31 is interpreted as an oil-water layer. After the middle 2m (1526.5-1528.5m) was reperforated and stable production is achieved, 28.0t of liquid and 5.4t of oil are produced with 95% water cut per day in the production zone. The results show that TNIS interpretation is correct with the results of 8.0t daily liquid increment, 5.4t daily oil increment and 32.5% water cut decreasing. TNIS interpretation results of each unit of well B are shown in Figure 2.
5. CONCLUSIONS

TNIS logging records thermal neutrons not captured by formation, and maintains relatively high residual thermal neutron counting rate in the formation with low salinity of formation water, which improves the calculation accuracy of capture cross section. In the processing, interpretation and evaluation of TNIS logging data, the interpretation model, interpretation parameters and interpretation criteria are established according to the geological characteristics of lithology and formation water salinity of the target block, which improves the interpretation coincidence rate. TNIS logging has achieved good results in Identification of flooded and potential layers, Re-examination of old wells and determination of remaining oil.

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