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A method to improve the sensitivity of neutron porosity measurement based on D-T source

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ABSTRACT

Compensated porosity logging tool utilizing deuterium-tritium (D-T) source shows a lower sensitivity to the variation of formation porosity compared with that adopting Am-Be source. In order to improve the sensitivity, the factors of an infinite homogeneous formation influencing slowing-down length and the near to far counts ratio are analyzed. Then Monte Carlo simulation method is used to build well logging models to study the responses of a neutron porosity logging tool to hydrogen index and formation density. It shows that in addition to hydrogen index, the variation of the density also has a great impact on slowing-down length and the ratio which reduces the response sensitivity to porosity. A new model depicts the relationship between the count ratio and porosity is proposed. When the model is used to process the measured ratio, the ratio shows improved dynamic range and sensitivity to porosity compared with the values without processing.

1. Introduction

Compensated neutron porosity logging technique adopting a neutron source and two or more neutron detectors to detect neutron counts is generally applied to determine formation porosity through measuring the hydrogen index. The relationship between the near to far counts ratio and porosity is generally established in calibration limestone wells to determine formation porosity. Two detectors are used to compensate the hole conditions (Alger et al., 1972; Allen et al., 1967; Ellis et al., 2003). Americium-Beryllium (Am-Be) is the most widely used neutron source for the compensated porosity logging tools in the past years. But due to the restriction and safety issues of Am-Be neutron source, D-T neutron source is being gradually adopted in the tools as D-T source can be electronically turned on and off and is free from the safety problems (Fricke et al., 2008; Jacobson et al., 2013; Peeples, 2007). In addition, by designing a specific burst timing cycle to control D-T source, other parameters such as macroscopic capture cross section can be determined as well as porosity in one running (Zhou et al., 2016). Porosity sensitivity is one of the most important parameter evaluating the performance of a specific neutron porosity logging tool. The energy of neutrons emitted from D-T sources is about 14 MeV which is significant higher than the average energy of the neutrons from Am-Be source. This leads to the different measurement sensitivities to porosity when these two sources are used. With the increasing of neutron energy, the interaction probability with hydrogen decrease quickly. That effect reduces the sensitivity of the ratio to porosity variation (Fricke et al., 2008; Peeples et al., 2010; Xu et al., 2009). By putting a neutron detector on the position with a specific distance from source which is called matrix density neutral distance, the effect of matrix density can be reduced when the ratio is adapted to determine porosity (Wraight, 1994). In addition, how the distance between source and the near detector or the distance between the two detectors affect porosity sensitivity is studied and the results show that the sensitivity increases monotonically with increasing of the interval spacing between the two detectors (Wu et al., 2013; Zhang et al., 2006). By correcting the effect of shale and lithology, sensitivity and accuracy of neutron porosity measurement also can be improved (Yu et al., 2014).

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Better response sensitivity is beneficial to the accurate determination of porosity. This paper focuses on a method to improve the porosity sensitivity when D-T source is adopted in a neutron logging tool. It will help improve the performance of neutron porosity instrument based on D-T source for accurate evaluation of porosity. First, the effects of hydrogen index and matrix of an infinite homogeneous formation on slowing-length and near to far counts ratio are analyzed. In addition, the responses of a specific porosity logging tool to various hydrogen index and formation density are simulated using Monte Carlo method and the modeling results are validated by experimental data. A new method reducing the density effect to improve the measurement sensitivity is proposed. Finally, the method is utilized to process continuous measurement data.

2. Factor influencing measurement response

According to the two-group neutron diffusion theory, for simple geometries, the near to far epithermal counts ratio, R, could be approximately described as (Allen et al., 1967; Scott et al., 1982):

$$R = \frac{N(r_1)}{N(r_2)} \approx \frac{r_2}{r_1} \cdot e^{-(r_1 - r_2)/L_s} \quad (1)$$

where $N(r_1)$ is the neutron count of near detector, $N(r_2)$ is the neutron count of far detector, r_2 is long spacing, r_1 is short spacing, and L_s is neutron slowing-down length.

Hydrogen index (*HI*) is defined as the quantity of hydrogen per unit volume relative to water at the standard condition. For clean fresh water saturated limestone, *HI* equals to porosity. Hydrogen concentration is supposed to dominate the slowing down of neutrons. By measuring the near to far neutron counting ratio, *HI* is inferred and related to porosity, since hydrogen is mostly present in the pore fluid. Environmental effects such as borehole size, mud *HI* and formation salinity should be considered when neutron porosity data is used to compare with core measurements.

The ratio is related to formation porosity using calibration data. When formation porosity is changed, *HI* and formation density dominated by other elemental atom density such as $CaCO_3$ are varied. Limestone is taken as an example and the parameters of different porosity formation are shown in Table 1.

In order to study the influence of those two factors on neutron slowing-down length and the count ratio separately, slowing-down lengths (L_s) of pure water with various density for the different energy neutron source are calculated using SNUPAR. SNUPAR is a computer code which can be used to calculate nuclear well logging parameters such as slowing down length and thermal neutron diffusion length of rocks with complex minerals and fluids. It has been validated by comparing with laboratory measurements and has been used for studying the effects of mineral mixtures and gas saturation on neutron log response (McKeon and Scott, 1989). In this study, the density of the water is artificially set to 0.05 g/cm^3, 0.1 g/cm^3, 0.15 g/cm^3, 0.2 g/cm^3, 0.25 g/cm^3, 0.3 g/cm^3, 0.35 g/cm^3 and 0.4 g/cm^3 corresponding to the same hydrogen index with water-saturated limestone formation as illustrated in Table 1 and the calculated slowing-down lengths are shown in Fig. 1.

Table 1
Parameters of limestone formations with various porosities.

Porosity/%	Hydrogen index	$CaCO_3$ mass in per cm^3 (g)
5	0.05	2.574
10	0.1	2.439
15	0.15	2.303
20	0.2	2.168
25	0.25	2.0325
30	0.3	1.897
35	0.35	1.7615
40	0.4	1.626

Fig. 1 illustrates that slowing-down length almost decays exponentially with *HI*. When *HI* is small, L_s has a quite large value. When *HI* is identical, the higher neutron source energy, the greater L_s of the formation is. When *HI* is 0.05, L_s is approximately 250 cm for D-T source. While for Am-Be source (average energy 4.5 MeV), it is only about 150 cm.

When the near and far spacing is set to 30 cm and 50 cm, the near to far counts ratios are calculated using Eq. (1) and are plotted as a function of *HI* in Fig. 2. The ratios increase rapidly as *HI* increases. The tendency is different from the realistic logging tool response, because the effects from borehole and tool itself are not accounted for. It is clear that the ratio for a low energy neutron source is more sensitive to the change of *HI*.

In the next step, the formation is set to pure $CaCO_3$ to study the effect of density on *Ls*, when hydrogen is not present. The overall density is set to 2.574 g/cm^3, 2.439 g/cm^3, 2.303 g/cm^3, 2.168 g/cm^3, 2.0325 g/cm^3, 1.897 g/cm^3, 1.7615 g/cm^3 and 1.626 g/cm^3 corresponding to same $CaCO_3$ molecular density when formation porosity is changed as mentioned in Table 1. The L_s are derived which is plotted as a function of density.

Figs. 3 and 4 show that in addition to the *HI*, the formation matrix also influences the neutron slowing-down length and the near to far counts ratio. It is inappropriate to relate the counts ratio to the hydrogen index alone. When the porosity increases, density of formation decreases and it will reduce the ratio value which is opposite to the effect of *HI*. This reduces the measurement sensitivity to porosity. In order to compare the effect of *HI* and $CaCO_3$ matrix on the ratio for various porosity formations, the relative contribution, R_c, is defined as:

$$R_c = \frac{R}{R_{CaCO3} + R_{HI}} \quad (2)$$

where R is the ratio when only water or $CaCO_3$ exists in the medium, R_{CaCo3} is the ratio when only $CaCO_3$ existing in the medium, R_{HI} is the ratio when only water exists in the medium. The relative contributions for 2 MeV neutron source and 14 MeV neutron source are calculated for the formation with different porosities as shown in Fig. 5.

Fig. 5 shows that for 14 MeV neutron source, the matrix contributes equally with the *HI* to the counts ratio at 25% porosity. When porosity is less than 25%, the recorded ratio is more affected by $CaCO_3$ matrix rather other *HI*. For 2 MeV neutron source, the corresponding critical porosity is about 12%. Therefore, it is

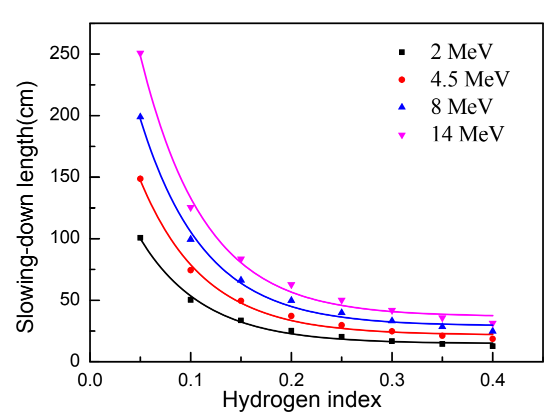

Fig. 1. Relationship between L_s and *HI*.