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

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A B S T R A C T

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):

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

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:

$$R_c = \frac{R}{R_{CaCO3} + R_{HI}} \tag{2}$$

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

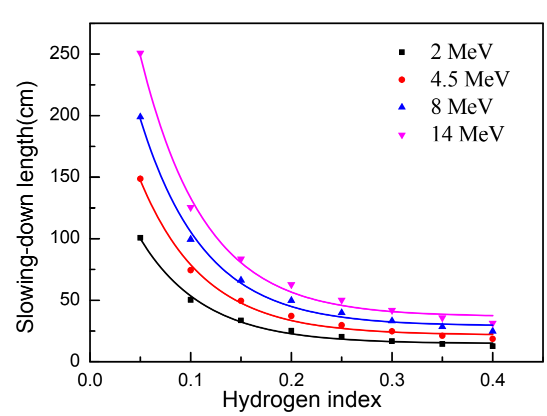

Fig. 1. Relationship between L_s and *HI*.

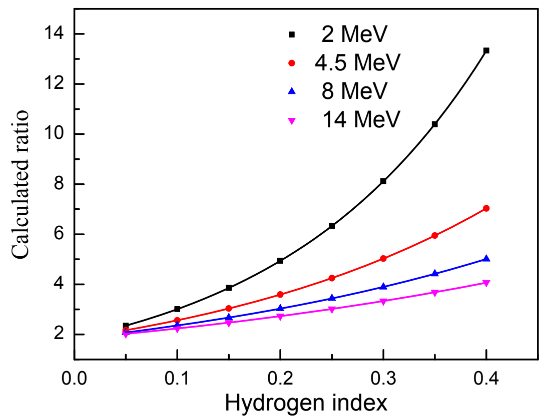

Fig. 2. Relationship between the calculated epithermal neutron counts ratios and *HI*.

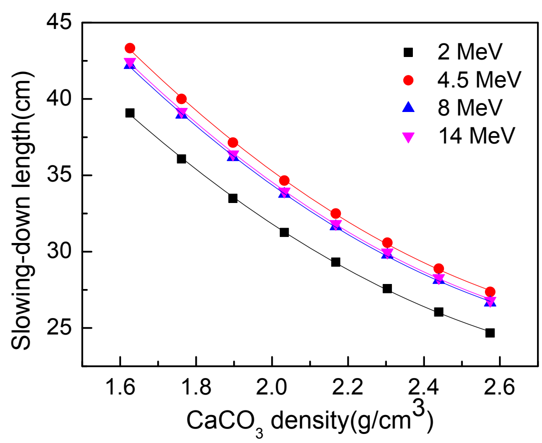

Fig. 3. Relationship between *Ls* and $CaCO_3$ density.

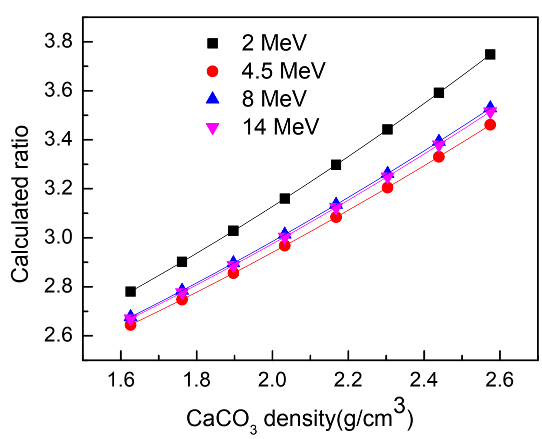

Fig. 4. Relationship between the calculated epithermal neutron count ratios and $CaCO_3$ density.

inappropriate to consider *HI* as the sole dominant factor of the neutron porosity logging response. Since high energy neutron source is less sensitive to *HI*, though it is slightly less sensitive to $CaCO_3$ density, the ratio is still more impacted by density compared with low energy neutron source. Therefore, the effect of density ought to be considered, particularly when D-T source is used in a neutron porosity logging tool. It is improper to interpret the

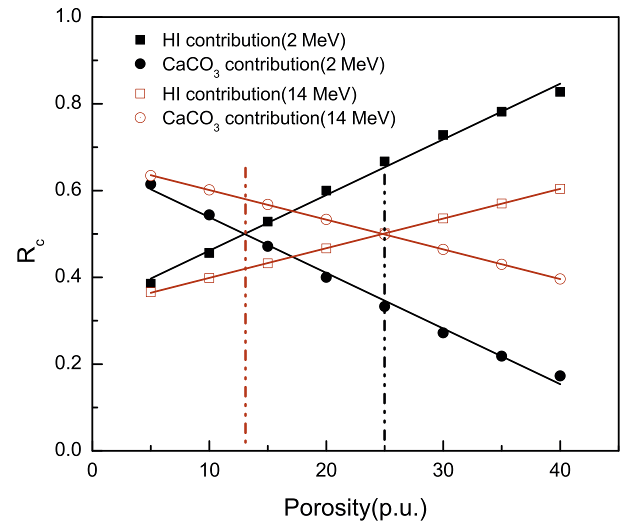

Fig. 5. Comparison between the effect and HI and $CaCO_3$ molecular density on the ratio.

measurement response by considering HI solely.

3. Method to improve the sensitivity

The MCNP code is a general-purpose Monte Carlo code which can be used for neutron, photon, and electron transport problems. It can deal with complex three-dimensional geometry and has been widely used in optimizing the parameters, logging response, and correction of influential factors of nuclear well logging instruments (Briesmeister, 1986; Galford et al., 2009; Goorley et al., 2012; Valant-Spaight et al., 2006). In order to study the response of the newly developed neutron porosity tool, the MCNP code is used in the modeling (Goorley et al., 2012). As shown in Fig. 6, the tool consists of two epithermal neutron detector and is pressed against the borehole wall. The short and long source-to-detector spacing is 30 cm and 50 cm, respectively. Borehole is filled with fresh water. Shielding materials are adopted between neutron source and near detector and between near and far detector.

Formation porosity is set to 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40% and pore is filled with fresh water with a density of 1.0 g/cm^3. Formation matrix is composed of $CaCO_3$ of which density is 2.71 g/cm^3. The near to far thermal neutron count ratios are computed as shown in Fig. 7. Five fixed point measurements using

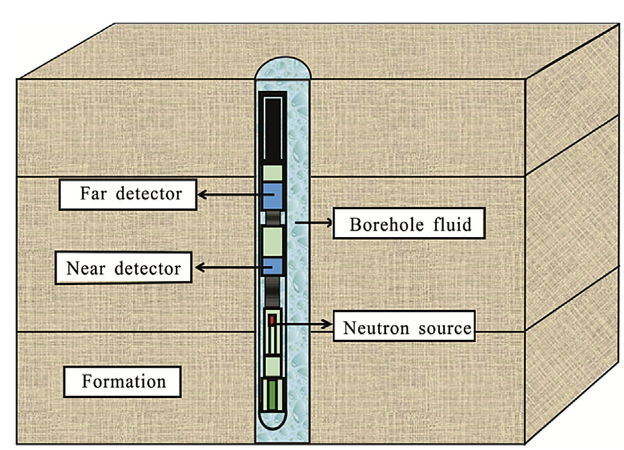

Fig. 6. Simulation model of porosity logging tool.

the newly developed tool in a calibration well are carried out. The corresponding porosity is 5%, 13.2%, 20.1%, 30%, and 37.2% respectively. Other specifications of the well are discussed in detail in Section 4. Experimental data are plotted as black point in Fig. 7.

As shown in Fig. 7, experimental and simulated data almost have the same tendency and agree with each other very well. This comparison validates the simulation, and allows the use of this modeling tool to study the response of the neutron porosity instrument. We can see that the ratio increases monotonically with increasing of porosity. The sensitivity of the ratio to porosity decreases with the increase of formation porosity. As illustrated above, in addition to the *HI*, the formation density also contributes to the value of *Ls* and the ratio. However, a quadratic polynomial model is generally used to describe the relation between the ratio and *HI* regardless of formation density effect. In this model, the near to far count ratio, *R*, is expressed as:

$$R = a \times HI^2 + b \times HI + c \tag{3}$$

where, a, b and c are polynomial fitting parameters, *HI* equals porosity in this logging situation.

In order to study the effect of *HI* separately, the same computation model is used and *HI* is set to 0.1, 0.2, 0.3 and 0.4. Meanwhile the molecular density of $CaCO_3$ remains unchanged. The ratio is supposed to be only related to *HI*. The relationship between the ratio and *HI* is obtained as shown in Fig. 8.

Fig. 8 shows that when only *HI* varies, the ratio increases with the increasing of *HI*. They have a good linear relation for the tool model used in the simulation. The responses of tools with different specifications would be different. The tendency in Fig. 8 is different from the data shown in Fig. 7, which further exhibits that measurement response is affected by the variation of density. Then formation models with different density are built with *HI* maintaining unchanged and the calculated ratios are shown in Fig. 9.

Fig. 9 shows formation density impact the ratio value and the ratio increases when density increases. In addition to the *HI*, density should also be taken into account to depict the ratio. Considering both the effect of *HI* and formation density, the model is modified as following:

$$R = (a \times HI + b) \times \left(c \times \rho^2 + d \times \rho + e\right) \tag{4}$$

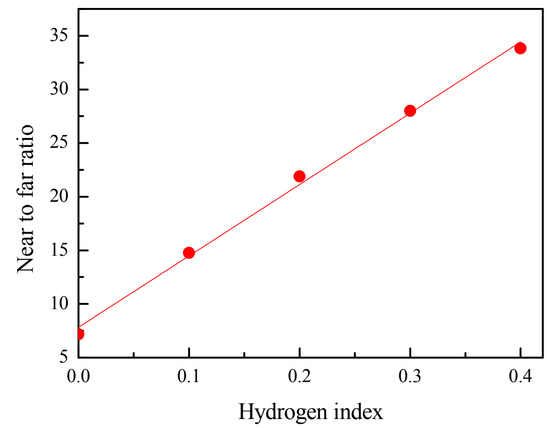

Fig. 8. Relationship between the ratio and *HI* for a specific porosity logging tool.

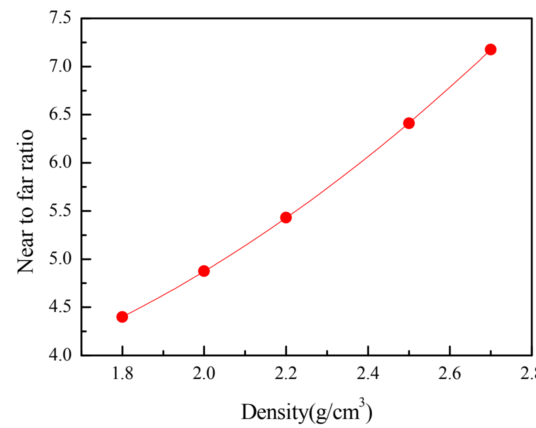

Fig. 9. Relationship between the ratio and density.

$$R_c = \frac{R}{c \times \rho^2 + d \times \rho + e} \tag{5}$$

where, a, b, c, d and e are multivariate nonlinear fitting parameters, ρ is density which could be determined by other logging method, R_c is the ratio after density correction. The modified model is used to process the data shown in Fig. 7 and the ratio responses before and

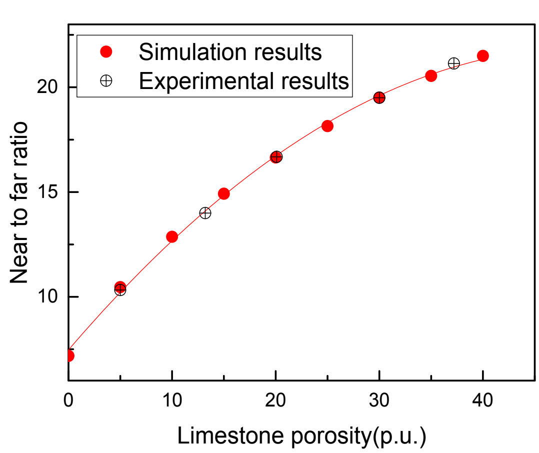

Fig. 7. Responses to formation porosity.

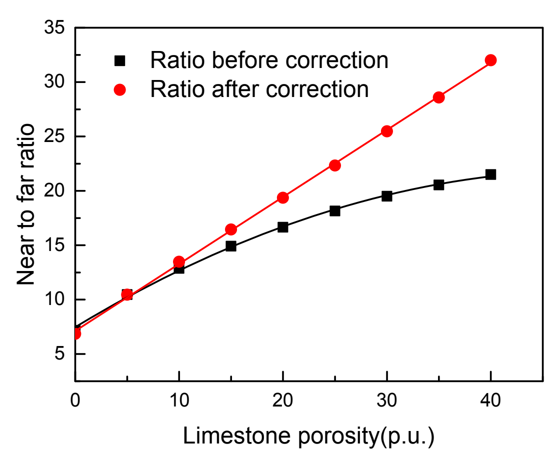

Fig. 10. The ratio value before and after density correction.

after processing are illustrated in Fig. 10.

From Fig. 10, it can be concluded that the ratio after processing is more sensitive to the variation of porosity compared with that without processing. The dynamic change D and measurement sensitivity S are calculated using the following formulas as shown in Table 2 (Liu et al., 2014).

$$D = \frac{R_{40} - R_0}{R_{40}} \quad (6)$$

$$S = \frac{1}{R}\frac{\partial \Omega}{\partial \phi} \quad (7)$$

where, R_{40} is the ratio when porosity is 40%, R_0 is the ratio when porosity is 0%, R is the count ratio, Ω is response function between ratio and porosity, ϕ is formation porosity.

The standard deviation of the porosity, $\Delta\phi$, can be expressed as:

$$\Delta\phi = \frac{\partial \Omega}{\partial R}\Delta R = (\Delta R/R)/S$$

where, ΔR is the standard deviation of R. Assuming the pulsed source strength is 2×10^8 n/s, the standard deviations of the porosity are calculated as shown in Table 2. The standard deviation of density is considered when R_c is used to calculate porosity.

From Table 2, it can be concluded the sensitivity gradually decreases with the increasing of porosity. When porosity is fixed, the sensitivity of the ratio after correction is significantly higher than the original ratio. The dynamic range of the corrected ratio is 0.78 which is about 1.2 times of the value without processing. When porosity is less than 10%, standard deviations of the porosity calculated by R_c are slightly larger than the results calculated by R method. When porosity is larger than 10%, the situation is reversed. The standard deviation of the porosity calculated by R method is about 3 times greater than the value of the new method when porosity is 40%. For conventional reservoir, the porosity of the stratum which we are interested in is usually larger than 10%. Therefore, the new method has advantage over the general method.

4. Continuous measurement example

Continuous measurement is carried out using the newly developed neutron porosity logging instrument adopting a D-T neutron source in a calibration well. The borehole dimeter of the calibration well is 200 mm and the borehole is surrounded by limestone rocks. The borehole is filled with fresh water and limestone are water-saturated. The pit is kept full of water all the time. The composition of the rock matrix is analyzed by chemical methods. The content of CaO and loss on ignition which is mainly composed of CO_2 is about 98.5% and the total concentration of the other oxides such SiO_2, Al_2O_3, TiO_2, Fe_2O_3 and MgO is less than 1.5%. The well consists of five limestone layers with different porosities as shown in Fig. 11. Porosities of the limestone rocks are obtained by core analysis, which are 5%, 13.2%, 20.1%, 30% and 37.2% respectively. The instrument is pressed against the borehole wall during the measurement and neutrons are measured by the two detectors. Other technical specifications of the calibration well are shown in Table 3.

The instrument is lifted from the bottom of the borehole and the neutron source is at the bottom side of the tool. Starting and ending points of the measurement are shown in Fig. 11(b). The position of the formation being investigated corresponds to the middle point between two neutrons detectors. Therefore, only part of the first and fifth layer is measured and the original near to far count ratios are shown in Fig. 11(a) as black line. The ratio response curves of the first and the fifth layer are shorter than that of the middle layers, and the curve corresponding to fifth layer is the shortest one. The measured ratio is processed using the method proposed in this article and the corrected ratio is shown as pink line in Fig. 11(a). It is observed that the ratio after correction has a lager dynamic range and is more sensitive to variation of the porosity compared with the ratios without processing, which will benefit the evaluation of formation porosity.

Table 2
Comparison of the ratio before and after density correction.

Porosity	R	S	$\Delta\phi_1$	R_c	S_c	$\Delta\phi_2$
0	7.182	8.06%	0.04	6.855	8.99%	0.09
5	10.463	4.98%	0.14	10.451	5.90%	0.17
10	12.867	3.60%	0.29	13.486	4.57%	0.29
15	14.919	2.71%	0.52	16.449	3.75%	0.44
20	16.649	2.08%	0.85	19.359	3.18%	0.62
25	18.147	1.59%	1.37	22.325	2.76%	0.86
30	19.506	1.18%	2.16	25.470	2.42%	1.13
35	20.544	0.84%	3.52	28.582	2.16%	1.45
40	21.498	0.53%	6.27	32.004	1.93%	1.82
D	0.66	–	–	0.78	–	–

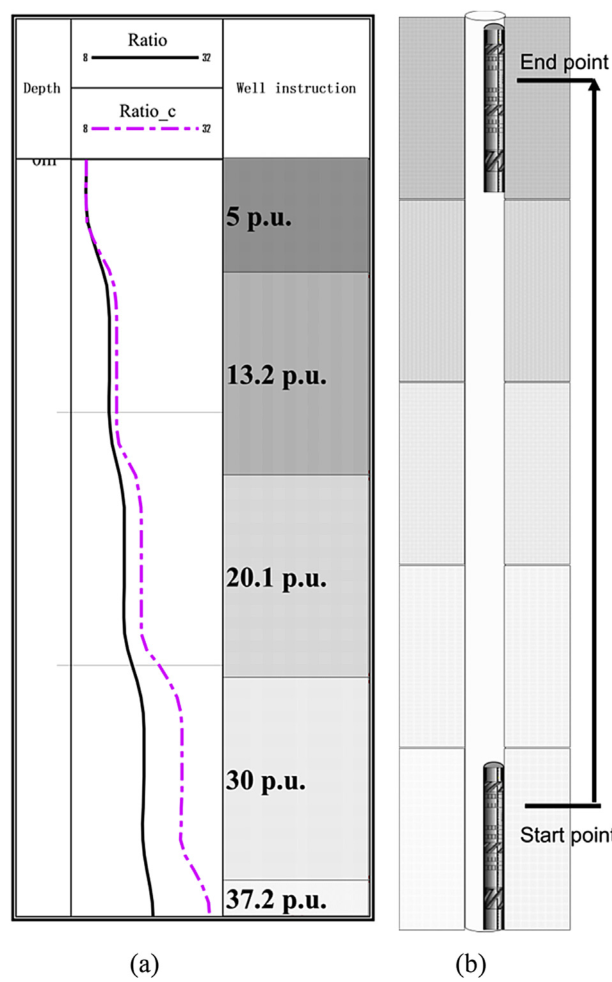

Fig. 11. (a) Comparison of the ratios before and after correction. (b) Measurement schematic of the instrument.

Table 3
Technical specification of the limestone calibration well.

Number	Porosity/p.u	Matrix density (g/cm^3)	Thickness/m
1	5.0 ± 0.5	2.705	1.6
2	13.2 ± 0.5	2.70	1.6
3	20.1 ± 0.5	2.71	1.6
4	30.0 ± 0.5	2.705	1.6
5	37.2 ± 1.0	2.703	1.6

5. Conclusions and future work

In addition to hydrogen index, the formation density also has an impact on neutron slowing-down length and the near to far counts ratio. It reduces the sensitivity of the counts ratio to variation of porosity. The ratio with Am-Be source used is more sensitive to change of hydrogen index than that with D-T source used. There is usually no need for performing density correction for Am-Be sources. However, this correction becomes significant for D-T source, due to its lower sensitivity to the variation of *HI*. In order to improve the sensitivity, a new model is proposed to correct the effect of density. It is utilized to process the recorded ratio in a test well and the ratio shows a better dynamic range and sensitivity compared with the values without processing.

As of now, only tests in calibration wells have been carried out. Validation of the proposed porosity estimation method in deeper oil wells and comparing the result with other logs are left to be carried out in the future. The proposed method can help the tool physicist to improve the performance of the neutron porosity well logging tools based on D-T source.

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