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A new diffusion effect correction method in pulsed neutron capture logging

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ABSTRACT

The neutron diffusion effect contributed considerate bias to the sigma estimation in the pulsed neutron capture (PNC) well logging, and thus this effect must be corrected to achieve an accepted sigma prediction. This paper developed a new diffusion effect correction method for a more accurate sigma estimation in the PNC well logging method. Since the diffusion effect with a given source spacing in a PNC tool mainly depends on neutron slowing down and absorption, two parameters, the capture gamma ray counts ratio (RCAP) of the far to near detectors and the gamma ray counts ratio of inelastic scattering to capture (RIC) in the near detector, were used in the new method to effectively correct the diffusion effect. This is because RCAP is sensitive to neutron slowing down ability and RIC is sensitive to thermal neutron absorption ability. A combined expression of RCAP and RIC thus can reflect both the scattering and absorption contribution to the diffusion coefficient, which is subsequently used to correct the diffusion effect. No additional efforts are required to measure RCAP and RIC because they can be simultaneously obtained with the gamma ray decay time spectrum measurement. Computational experiments based on Monte Carlo simulations demonstrated the sigma calculated with the new correction method has shown to be more accurate than the non-corrected apparent sigma in the PNC logging.

1. Introduction

Pulsed neutron capture (PNC) logging technique has been used for decades in nuclear well logging for oil saturation calculation (Youman et al., 1964; Allen et al., 1986; Steinman et al., 1988). Because the salinity water has a higher radiation capture cross section than that of oil or gas, the gamma ray or thermal neutron will decay slower when the porosity is saturated with oil or gas. Therefore, by examining the gamma ray or thermal neutron time decay spectrum and estimating the decay coefficient (i.e., sigma) of a formation under the irradiation of a neutron source, the oiliness of the formation can be inferred (Mimoun et al., 2011; Randall et al., 1983). This technique is known as the PNC sigma logging method, or short as the sigma method. If applied to middle to high water salinity formation, the sigma method is considered to be more robust and statistically more precise than the conventional Carbon/Oxygen logging method because its sensitivity to the amount of salinity. However, the radiation loss due to the particle diffusion effect in the formulation has imposed a tough challenge to the sigma method (Badruzzaman et al., 2010; Rose et al., 2015; Schmid et al., 2018).

The mechanism of diffusion effect on the sigma method can be physically explained as follows. The decay of the gamma ray or thermal neutron counts is not only caused by absorption, but also by the count loss due to the radiation particle diffusion through the formation (Roberts, etc., 2010; Lou, etc., 2004). The diffusion of neutron or gamma ray in a homogeneous medium leads to spatial variation of the neutron or gamma ray flux. Depending on the geometry of the one-source two-detector logging system, the influence of diffusion effect on the sigma method has shown different directions. The effect will be positive in the near source spacing case, and negative in the far source spacing case (Mlckael et al., 1999). This distinct influence of diffusion effect on sigma for different cases is confirmed later in Section 2.2, in which quantitative justifications are provided by Monte Carlo simulations. Because the diffusion effect is sensitive to the source spacing, substantial efforts are required for engineers to identify a balanced source spacing to compute the optima sigma so that the diffusion effect can be neglected. Furthermore, the balanced point in the logging geometry will usually be

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different in various porosity or salinity and cannot be determined readily. Thus repeated efforts are envisioned for different situations. Due to these reasons, more efficient diffusion effect correction methods for the sigma calculation are demanded.

In this work, a new diffusion effect correction method for the PNC sigma logging is proposed.This method develops a quick means to correct the diffusion effect using two parameters based on two-source spacing gamma ray detector counts. One parameter is ratio of the capture gamma ray counts for the near and far detector (RCAP). Another is the gamma ray counts ratio of inelastic and capture (RIC) in one single detector (usually the near spacing one). These two parameters are used because the RCAP is sensitive to neutron slowing down ability and the RIC is sensitive to thermal neutron absorption ability. A detailed description of diffusion effect correction procedure is provided in the method section (Section 3). After the diffusion correction, one can expect more accurate sigma results compared with the intrinsic sigma.

The rest of the paper is organized as follows. Some technical requirements to understand the diffusion correction method are introduced in Section 2, followed with a more detailed description of the theory and method for the diffusion effect correction. Results of couple of example problems after applying the proposed diffusion correction method are presented in Section 4. Some conclusions of this work are offered in the last section.

2. Technical background

2.1. Time decay spectrum and sigma

In the PNC sigma logging, neutron source pulsing high energy neutrons into the borehole and formation for a brief period. These neutrons will be slowed down and thermalized through repeated collision, and then captured by isotopes in the formation. As each neutron is captured, gamma rays are emitted. The rate of capture gamma rays is proportional to the density of neutrons, which decreases with time. By measuring the gamma ray counts in different time bin, time decay spectrum of gamma ray is obtained. Dual exponential fitting method (Schmid et al., 2018) is usually used to convert the time decay spectrum to sigma. The equation for the fit is

$$N(t) = A_{BH} \times \exp(-t \cdot \nu \Sigma_{BH}) + A_{FORM} \times \exp(-t \cdot \nu \Sigma_{FORM}) \quad (1)$$

where $N(t)$ is gamma ray counts in a time bin, A_{BH} and A_{FORM} are the count amplitudes contributed from the borehole and formation, ν is the averaged thermal neutron speed (2200 m/s is used in the calculation), Σ_{BH} and Σ_{FORM} are the apparent sigma for the borehole and formation. The unit of sigma is an equivalent alternative to the mass-normalized macroscopic cross section and is usually referred to as the capture units (c.u.), which is essentially 1000 times of the mass-normalized macroscopic cross section (namely, 1 c.u. $= 10^{-3}$ cm^{-1}).

The fit is performed using a weighted least squares minimization technique. Once the fitting is complete, the apparent borehole sigma and apparent formation sigma can be calculated. This is done for each detector, resulting in a Σ_{FORM} for near and far: Σ_{near} and Σ_{far}. These sigma's are referred to as "apparent" in the definition of Eq. (1) because they are not yet corrected from the diffusion effect.

Monte Carlo based computational simulation is an efficient means to produce the time decay spectrum of gamma ray and sigma, and to understand the diffusion effect on the sigma method. In this work, MCNP (X-5 Monte Carlo Team, 2003) a generic 3D Monte Carlo particle transport code developed by LANL, is employed to perform all the simulations. Fig. 1 illustrates the simplified cylinder-shaped PNC sigma logging model used in this study. As indicated in the figure, the logging model consists of a formation matrix, the borehole, and a PNC logging tool. The formation matrix is composed of either sandstone or limestone. For study purpose, the porosity and water salinity in the formation will be varied to form different intrinsic sigma values for the model. The PNC logging tool consists of one D-T neutron source, the tungsten shield, and the near and far gamma ray detectors. The near source spacing is 36 cm, and the far source spacing is 56 cm. The D-T neutron source will be emitting neutrons during 0–200 us within a measurement time period of 1800 us. Near and far gamma ray detector are used to record the gamma ray counts in different time bins. Inelastic gamma ray counts are record between 0 and 200 us, and capture gamma ray are record between 600 and 1800 us.

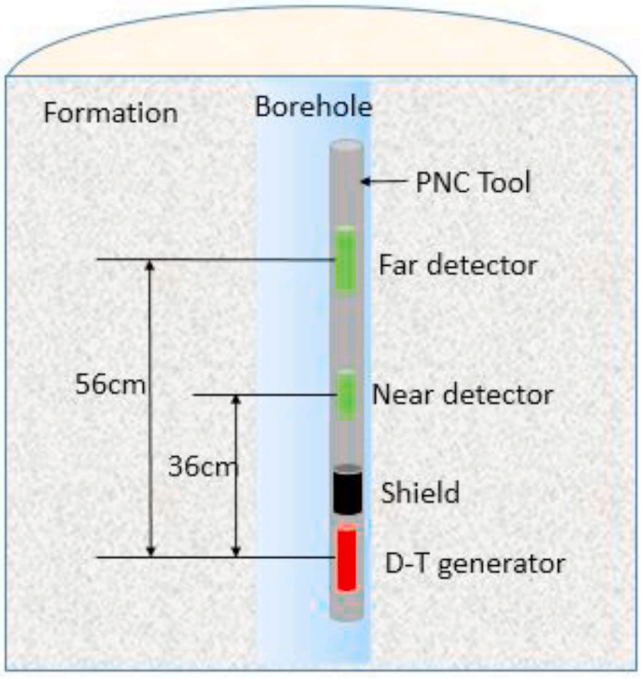

Fig. 1. Schematic diagram of a PNC sigma logging model.

To understand the formation porosity and salinity effect on sigma, the response of time decay spectra for various formation porosities and salinities are studied in this part using the Monte Carlo simulations described above. In the first case, the water salinity is set as 50 g/L, and the porosity is varied as 5%, 20% and 40%, respectively. In the second case, the porosity of the formation is set as fixed 20%, and the salinity is varied as 0 g/L, 100 g/L and 200 g/L, respectively. Limestone is used as the formation rock matrix for both cases. The time decay spectra recorded by the near gamma ray detector for both cases are shown in Fig. 2(a) and Fig. 2(b), respectively. The corresponding intrinsic sigma (real sigma) associated with each decay spectrum is presented in Fig. 2.

As shown in Fig. 2(a), since salinity water has higher capture cross section than limestone, the gamma ray time decay degree will increase with the increase of porosity. Porosity will also effect on the inelastic gamma ray counts. Hydrogen in the water has the higher neutron slowing down ability than other element. Hence, fast neutrons are easy to be slowed down in the high porosity formation that leads the decrease of the inelastic gamma ray counts. On another hand, as shown in Fig. 2 (b), since Chlorine in the salinity water has higher capture cross section than other common element (except boron, gadolinium etc.) in the formation, the higher water salinity formation has higher gamma ray counts decay degree. It also can be seen that the inelastic gamma ray counts are less effected by water salinity when there has the same porosity.

2.2. Diffusion effect on sigma

Under the PNC sigma well logging conditions, the diffusion effect on sigma with different source spacings is different. The diffusion effect will also be affected by the formation condition, particularly the porosity and

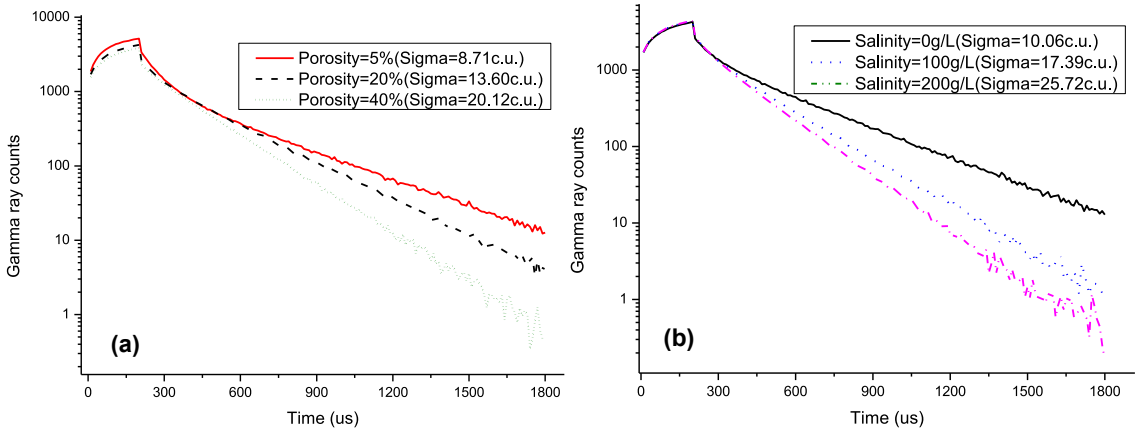

Fig. 2. Gamma ray time decay spectra with various formation porosities (a) and water salinities (b).

water salinity property studied earlier. MCNP simulation can also be used to understand these effects. In the following study case, time decay spectra with different source spacings varied from 26 cm to 76 cm are calculated. The sigma at different source spacings are also calculated and compared in three specific intrinsic sigma (real sigma) condition. The lithology used in the study is limestone. The results of the test case is depicted in Fig. 3.

When the formation porosity is 10%, and water salinity is 0 g/L, the relationship between source spacing and diffusion sigma (sigma caused by diffusion) is shown as the black solid line in Fig. 3. It can be seen that both the near and far source spacing presents positive diffusion effect for this case. When the formation porosity is 30%, and water salinity is 150 g/L, the relationship between source spacing and diffusion sigma is shown as the dashed red line in Fig. 3. It can be seen that the near source spacing presents positive diffusion effect, and the far source spacing presents negative diffusion effect. When the formation porosity is 40%, and water salinity is 200 g/L, the relationship between source spacing and diffusion sigma is shown as the dotted blue line in Fig. 3. It can be seen that both the near and far source spacing presents negative diffusion effect. It can also clearly seen from Fig. 3 that the diffusion sigma is generally decreasing with the increasing of source spacing.

The reason for these phenomena can be explained as follows. For a closer neutron source spacing, the flux of thermal neutrons is always larger particularly for the case the formation has lower neutron slowing down and absorption ability. Under such a scenario, one can envision the primary loss mechanism for thermal neutrons will be the pattern of diffusion. However, with the increasing of source spacing, the flux of thermal neutron is decreasing exponentially. As a result, more percent of thermal neutrons will be lost by absorption, and the diffusion sigma will decrease. In another case, when the formation has strong ability to slow down and absorb neutrons, most of the neutrons in the near source spacing will be lost in the pattern of absorption, which makes the diffusion sigma even more less in the near source spacing. In the extreme case, the neutron loss due to slowing down and absorption is so strong that would anyhow lead to the low thermal neutron flux at different source spacing's. Therefore, the formation absorption ability cannot be fully expressed, which leads to the negative diffusion effect.

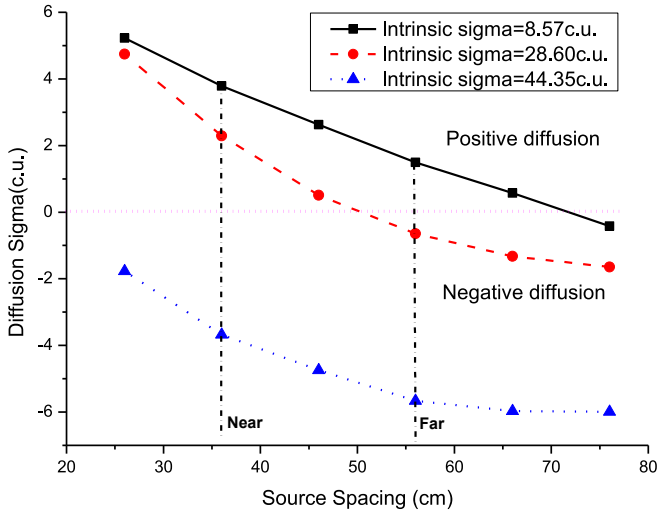

Fig. 3. Relationship between source spacing and diffusion sigma.

3. Diffusion correction method

In the PNC sigma logging, the neutron generator typically works in a pulsing mode to emit high energy (14.1 MeV) neutrons. Shortly after the pulse, these high energy neutrons will be slowed down and become thermal neutrons in most of their lifetime. The thermal neutron population along the time will decline by the way of absorption or diffusion. The time-dependent diffusion equation governing the density of thermal neutrons may be described as

$$\frac{1}{n}\frac{\partial n}{\partial t} = -v\Sigma + Dv\frac{\nabla^2 n}{n}, \tag{2}$$

where n represents the thermal neutron density, Σ is the thermal neutron absorption cross section, and D is the thermal diffusion coefficient. The term $Dv\frac{\nabla^2 n}{n}$ represents the diffusion effect of the thermal neutrons and has been ignored in the earlier global analysis (Badruzzaman et al., 2010), which is the underline culprit that causes errors in the sigma logging method.

As indicated by Eq. (2), the global behavior of the neutron population will decay exponentially with the time. If we assume the apparent decay time of the neutron population τ_a satisfy the follows

$$\frac{\partial n}{\partial t} = -\frac{n}{\tau_a}, \tag{3}$$

and define the intrinsic time constant τ_{int} and the diffusion time constant τ_{diff} as follows, respectively,

$$\frac{1}{\tau_{int}} = v\Sigma, \tag{4}$$

$$\frac{1}{\tau_{diff}} = -Dv\frac{\nabla^2 n}{n}. \tag{5}$$

Based on Eq. (2), the apparent decay constant can then be expressed as sum of the intrinsic time constant and a diffusion time constant

$$\frac{1}{\tau_a}=\frac{1}{\tau_{int}}+\frac{1}{\tau_{diff}}. \tag{6}$$

Based on the relationship between capture cross section and time constant, Eq. (6) can be re-written as

$$\Sigma_a=\Sigma_{int}+\Sigma_{diff}, \tag{7}$$

where Σ_a is the apparent sigma (measured sigma), Σ_{int} is the intrinsic sigma and Σ_{diff} is the diffusion sigma that need to be corrected. Eq. (7) clearly indicates the diffusion effect will possibly lead the result of measured Σ higher (positive diffusion effect) or lower (negative diffusion effect) than the intrinsic value.

Diffusion sigma can be represented as

$$\Sigma_{diff}=-Dv\frac{\nabla^2 n}{n} \tag{8}$$

From the transport theory of transport and absorption (Ellis et al., 2007), the diffusion coefficient can be expressed as

$$D=\frac{1}{3(\Sigma_t-\overline{\mu}_0\Sigma_s)}, \tag{9}$$

where Σ_t is the total macroscopic cross-section, Σ_s is the scattering macroscopic cross-section, $\overline{\mu}_0$ is the average cosine of the angle in the system.

According to Eq. (8), if the stationary source spacing and logging geometry are determined, the diffusion sigma will mainly depend on the diffusion coefficient *D*. According to Eq. (9), the diffusion coefficient *D* is a parameter that would be impacted by both scattering cross section and absorption cross section. Thus to accurately estimate the diffusion sigma, two parameters to characterize the neutron scattering and absorption effect respectively need to be selected. The RCAP and RIC that are readily obtained in the PNC logging are selected in our method to serve these roles. The reason why these parameters are used and the way of using the responses of RCAP and RIC with different porosities (different neutron scattering ability) and water salinities (different neutron absorption ability) to correct the diffusion effect in the sigma method are outlined in the following.

First, we noticed the different characteristics of RCAP and RIC in response to the porosity of the formulation. Fig. 4 shows the porosity relationship with RCAP and RIC in different water salinity environments. These results are obtained by Monte Carlos simulations using the same experimental configuration described in Section 2.1. As can be seen from the figure, the RCAP is monotonically increasing with the increasing of porosity and has less effect by the water salinity. Whereas the RIC variation tendency is diverse in different water salinities when formation porosity is increased, which indicates that the water salinity has greater effect on the RIC. The observations on the different responses shown in Fig. 4 confirm the facts that RCAP is more sensitivity to the neutron scattering ability and the RIC is more sensitivity to neutron absorption ability.

The distinct response behaviors of RCAP and RIC to porosity and water salinity makes them two appropriate parameters to correct the diffusion effects by taking a combination of these parameters. As a standard practice, using RCAP to reflect the neutron slowing down length and RIC to reflect the neutron absorption, the diffusion sigma Σ_{diff} can be reproduced as

$$\Sigma_{diff}=\alpha\cdot RCAP+\beta\cdot RIC, \tag{10}$$

where α and β are undermined coupling coefficients that will be affected by the source spacing. For a given source spacing condition, these coefficients can be calculated and calibrated using Monte Carlo simulations. In the real logging tool, the source spacing of two detectors is stationary. The calibration coefficient of near and far detector can be computed with the standard least squared method. At the last step, the corrected sigma is calculated with an arithmetic average of near and far gamma ray detector measures.

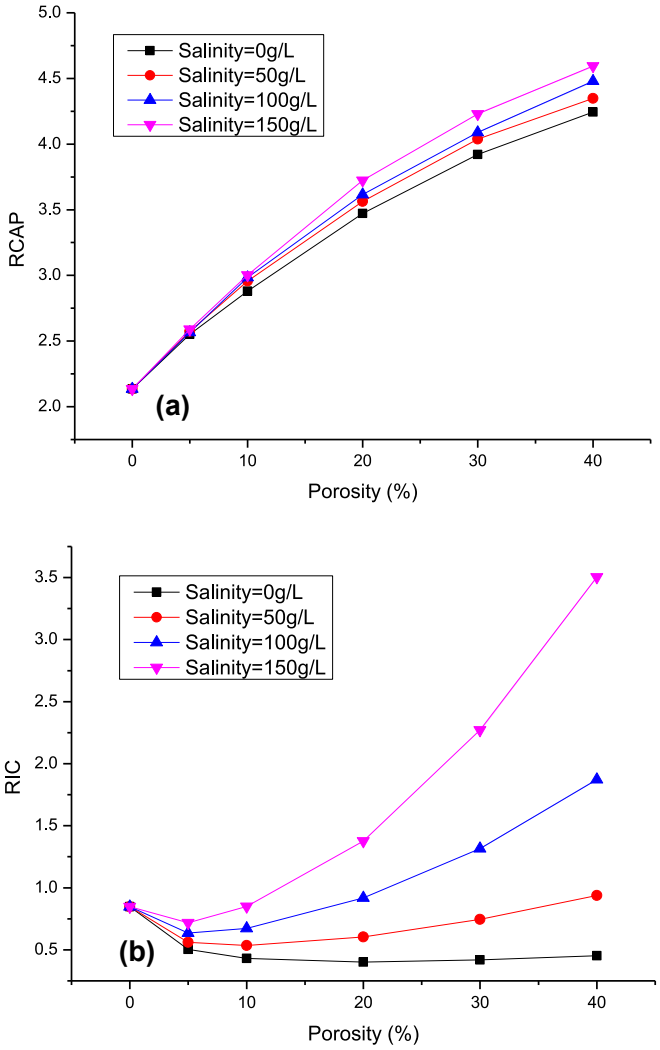

Fig. 4. Porosity relationship with RCAP (a) and RIC (b) in different water salinities.

4. Computational results

Efforts on the validation of the diffusion correction method described above were undertaken. Both computational and experimental results were employed to justify the efficiency and viability of the proposed method in PNC sigma logging. This section presents the procedures and results of the validation efforts.

First, computational models with different lithology, porosity and salinity conditions were built with MCNP to obtain the calibration coefficients and verify the diffusion correction method. The basic configuration of the computational model is described in Section 2.1, whereas the lithology, porosity and salinity conditions used in the simulations are shown in Table 1. As three independent parameters, lithology, porosity and salinity can be set with different permutation and combination.

Table 1
Lithology, Porosity and Salinity Conditions Used in the MCNP models.

Parameter	Value
Lithology	Sandstone, Limestone
Porosity (%)	0, 5, 10, 20, 30, 40
Formation water salinity(g/L)	0, 50, 100, 150, 200

Hence, 60 data points are simulated in this validation test. These models are developed purposely to include materials with the intrinsic sigma ranging from 4 c.u. to 45 c.u., which covers the majority of the common known formation conditions.

The apparent sigma of different formation situations in the near and far spacing detectors were calculated based on the MCNP simulation results. Fig. 5 compares apparent sigma with the known intrinsic sigma in a correlated manner, where the exactly correlated curve (in such cases the intrinsic sigma are identical to the apparent sigma) is shown with a dashed red line. As shown in Fig. 5, non-negligible discrepancies between apparent and intrinsic sigma in many different formation situations are clearly observed, no matter these apparent sigma are obtained from near or far spacing detectors.

Using the simulation data and the diffusion correction method described in Section 3, the calibration coefficients of near and far detectors were calculated by least squared method, and the results are shown in Table 2.

Using these coefficients as well as the simulated RCAP and RICA values, the diffusion sigma can be calculated following Eq. (10), and then the sigma in the near and far source spacing in different formation conditions were corrected following Eq. (7). Fig. 6 compares the corrected sigma calculated with intrinsic sigma in the same matter as that of Fig. 5. As can be seen in Fig. 6, the accuracy of sigma results obtained after the diffusion correction are considerably improved in nearly all formation conditions in the tests. Be more quantitatively, before the correction, the average relative error in different formation simulation conditions of apparent sigma is 30.08% for the near detectors and 13.88% for the far detector. After the correction, the average relative error of corrected sigma is reduced to 2.36%.

The feasibility of the new diffusion correction method was further validated by physics experiments. At this stage, the sigma diffusion correction method was applied to the PNC logging tool test data, which were measured from five calibration wells with known borehole and formation conditions. The borehole was filled with fresh water. Limestone was the formation used in all five wells, but porosity of the limestone was maintained to be 0.2%, 12.8%, 18.2%, 21.4% and 27.5%, respectively. During the PNC logging experiments, the PNC logging tool measured the time decay spectrum of near and far detector. It also simultaneously measured the RCAP and RIC values, which would be used to generate the calibration coefficients. Apparent sigma of near and far sigma were calculated directly from the time decay spectra, and corrected sigma were also calculated using the new diffusion correction method introduced in this paper. Both apparent sigma and correct sigma are shown in Fig. 7, in a similar manner correlating to the intrinsic sigma of known formulations. It can be seen from the figure that the corrected sigma is much more accurate than apparent sigma.

Table 3 summarizes the relative error of apparent sigma and corrected sigma comparing to the intrinsic sigma in all experiments. It can

Table 2
Calibration coefficients of the near and far detector.

Coefficient	α	β
Near detector	11.23	−0.52
Far detector	6.51	−0.91

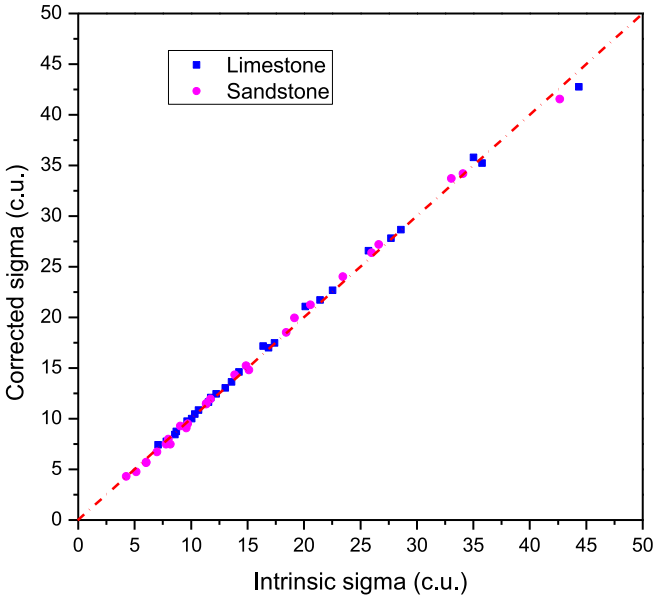

Fig. 6. Correlations of the intrinsic sigma and corrected sigma.

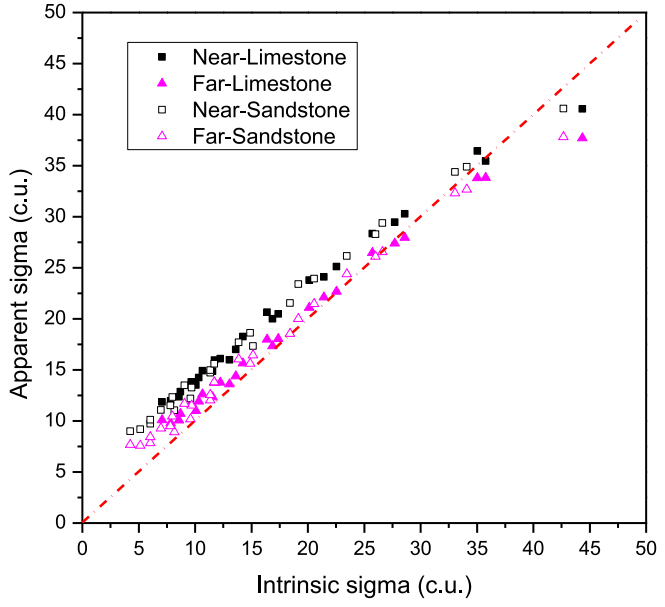

Fig. 5. Correlations of the intrinsic sigma and apparent sigma in different detectors.

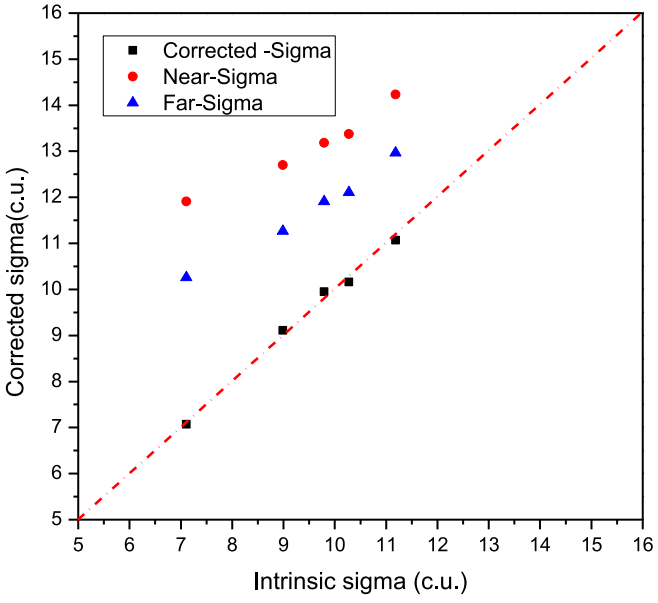

Fig. 7. Correlations of the intrinsic sigma, apparent sigma from detectors, and corrected calculated sigma in calibration wells.

Table 3
Deviations existed in the apparent and corrected sigma.

Well #	Porosity (%)	Near apparent sigma relative error (%)	Far apparent sigma relative error (%)	Corrected sigma relative error (%)
1	0.2	65.50	44.32	0.53
2	12.8	41.30	25.32	1.30
3	18.2	34.59	21.60	1.55
4	21.4	30.16	17.86	1.10
5	27.5	27.25	15.94	1.01

be seen that the relative error of near and apparent sigma are remarkably higher than corrected sigma. Particularly, the relative error are much higher when there has a low formation porosity. Because the low porosity formation has weak neutron scattering and absorption ability, most of the neutrons disappear by the way of diffusion, which lead great diffusion effect need to be corrected, especially in the near detector.

5. Conclusions

This paper proposed a new diffusion effect correction method for a more accurate sigma calculation in the PNC sigma logging method. The diffusion effect could entail either positive or negative contribution to the sigma depending on the formation condition. Low porosity and low water salinity would often lead to positive diffusion, whereas high porosity and high water salinity could lead to negative diffusion. By using the parameters of RCAP and RIC simultaneously measured with the gamma ray decay time spectrum, the diffusion sigma can be reproduced and used to correct the diffusion effect in sigma estimation. This is because the parameter of RCAP can reflect the neutron scattering effect in the formation, while the parameter of RIC can reflect the thermal neutron absorption effect in the formation. A combined expression of RCAP and RIC thus can reflect both the scattering and absorption contribution to the diffusion coefficients, which is subsequently used to correct the diffusion effect. Computational experiments showed the sigma is calculated with more accuracy results compared to the intrinsic sigma after the correction is exercised with the proposed diffusion correction method.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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