Introduction

With the increase in global energy demand, the unconventional oil & gas is one of the ways to ease the future energy crisis. Hydraulic fracturing technology is the main method to improve the oil and gas recovery of unconventional oil and gas formations with low porosity and low permeability. Accurate evaluation of fracturing effects including parameters such as fracture height and density is of great significance for oil and gas stimulation, optimization of fracturing models, and repeated fracturing. In the near-well area fracture evaluation, there are mainly sonic logging, well temperature logging, electrical imaging logging, etc., but the applications of these technologies are limited due to the effects of casing, cement rings and other factors in casing wells. In nuclear logging, fast neutrons emitted by D-T can easily penetrate casing and cement rings and directly interact with the nucleus of the medium. And it is less affected by the casing cement ring, which can achieve accurate evaluation of fracture parameters near the well. In 2007, McDaniel first proposed that the proppant with high thermal neutron absorption capability and a compensated neutron instrument or pulsed neutron instrument are combined to hydraulic fracturing fracture evaluation. Because of its non-radioactive pollution, measurement without time limit, repeatable multiple measurements and strong operability, it has attracted wide attention. At present, this technique can be used to accurately calculate the fracture position and height by comparing the difference in neutron or gamma counts before and after fracturing. However, due to the influence of neutron self-shielding, the detection depth of the instrument is shallow and the calculation is not accurate when the fracture density is large.

A new enhanced method of non-radioactive hydraulic fracturing fracture density based on neutron self-shielding correction is proposed in this paper. Firstly, the proppant with high thermal neutron absorption capability and pulse neutron tool (PNT) are combined to obtain the time spectrum and energy spectrum of formation before and after hydraulic fracturing. Secondly, the self-shielding coefficient is calculated by internal calibration of element characteristic peak counts from energy spectrum. Thirdly, the macroscopic capture cross section calculated by time spectrum of gamma is corrected by the self-shielding coefficient. Furthermore, the mathematical relationship established between the macroscopic capture cross section and the fracture density is used to achieve the accurate evaluation of the fracture density. Finally, a continuous depth simulation example containing different location and density of fracture verifies the feasibility of the method.

Method and/or Theory

The \( \gamma \)-ray count obtained by reacting the nucleus in a volume with a solid angle of dV per unit time and solid angle can be written as

\[
dn(\gamma) = \phi_\Omega d\Omega e^{-\Sigma_A} d\gamma \frac{\rho}{M} N_A \sigma \varphi e^{\Sigma_N \sqrt{x^2 + y^2 + z^2}} dxdydz
\]

(1)

Where \( M \) is the relative molecular mass of the sample nuclide; \( \Sigma_S \) is the macroscopic absorption cross section of formation after hydraulic fracturing at a certain energy; \( \rho \) is the density of the sample; \( N_A \) is the Avogadro constant; and \( \sigma \) is the differential section of the characteristic \( \gamma \)-ray. When the neutron self-shielding effect is not considered, its \( \gamma \)-ray count can be expressed as

\[
dn'(\gamma) = \phi_\Omega d\Omega e^{-\Sigma_A} \varphi e^{\Sigma_N \sqrt{x^2 + y^2 + z^2}} dxdydz
\]

(2)

Where \( \Sigma_0 \) is macroscopic absorption cross section of formation before hydraulic fracturing. The neutron self-shielding coefficient \( f_s \) can be defined as
\[
 f_n = \frac{\int dn(y)}{\int dn'(y)} = \frac{\iiint ye^{-\gamma(\sqrt{x^2 + y^2 + z^2})} \, dx \, dy \, dz}{\iiint ye^{-\gamma(\sqrt{x^2 + y^2 + z^2})} \, dx \, dy \, dz}
\]

The effective detection area of the instrument is constant, so the coordinates of x, y, and z in Eq.3 can be determined. Moreover, the content of high thermal neutron capture cross-section elements in proppants is known. It is assumed that the neutrons generated by the neutron source are unified as thermal neutrons, and the change in the neutron absorption cross section caused by the energy reduction caused by the elastic scattering process of the neutron and the sample is not considered. The response of the neutron self-shielding factor and the macroscopic capture cross section can be calculated by further simplification, which are shown in Figure 1. It is indicated that the stronger the neutron capture capability of the medium, the more obvious the self-shielding effect in Figure 1.

![Figure 1](image)

**Figure 1** The response of Self-shielding factor correction coefficient to macroscopic captured cross-section of materials.

**Results and Discussion**

The Monte Carlo N-particle transport code (MCNP) has been widely used in studies to optimize parameters and responses of different nuclear well logging tools (Liu et al., 2014). The MCNP was employed to build the fracturing formation models shown in Fig.2 to simulate the response of fracture density, and the specific model parameters are as follows: The borehole with a diameter of 20 cm consists of the casing and cement, and it is filled with pure water. The diameter of the tool is 49 mm, and the spacings of near, far, and long detector are 32 cm, 55 cm and 70 cm, respectively. During the whole measurement, the instrument is placed in the center of the borehole. The fracture is filled with tagged proppant and pore fluids such as fresh water, oil and gas. The tagged proppant is mainly composed of quartz sand and boron carbide. The fractures containing tagged proppants were generated randomly in model.

Using the MCNP calculation model established in Figure 2, the fracture densities were set to 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10%, respectively. The gamma energy spectrum and the time spectrum captured gamma are recorded by special timing design. The time spectrum of the six fracture densities are shown in Figure 3. As shown in Figure 3, due to the pulsed emission, the capture gamma started to increase rapidly. After the pulse stops, the captured gamma decays exponentially. Furthermore, with the increase of fracture density, the decay rate of captured gamma increases violently. When the fracture density exceeds 5%, the captured gamma declines and the radiological
statistical error increases. The time spectrum are used to calculate the macroscopic captured cross section of formation by double exponential fitting method.

The Figure 4 shows the response of macroscopic capture cross section to fracture density before and after correction of neutron self-shielding effect. When the fracture density increases from 0 to 10%, the macroscopic capture section increases by 7.4c.u without correction. However, the fracture density increased from 4% to 10%, and the macroscopic capture cross-section increased by 1.1c.u. Because of the neutron self-shielding effect, the macroscopic capture cross section quickly reach saturation. So when the fracture density exceeds 5%, it is extremely inaccurate to directly inverse the fracture density from the original data. The self-shielding coefficient in Figure 1 was used to correct the response of fracture density, and the results are shown in Figure 3. After correction, the macroscopic capture cross section of the formation increased linearly with the increase of fracture density. The macro-capture cross-section saturation effect caused by self-shielding is eliminated. After self-shielding coefficient correction, macro-capture cross section is used to inverse fracture density with high accuracy. So the fracture density inversion formula can be written

\[ \rho_{\text{fracture}} = a \times \sum_{n} f_n + b \]  

(4)

Where \( \Sigma \) is macroscopic absorption cross section of formation after hydraulic fracturing, \( f_n \) is the neutron self-shielding coefficient, \( \rho_{\text{fracture}} \) is fracture volume density.

![Figure 2](image1.png)  
**Figure 2** The numerical calculation model of fractured formation by MCNP

![Figure 3](image2.png)  
**Figure 3** The time spectrum response of different fracture density

![Figure 4](image3.png)  
**Figure 4** The response of macroscopic capture cross section to fracture density before and after correction of neutron self-shielding effect
A fracturing formation model with a continuous depth was established by MCNP. The depth of formation is 550cm, which consists of four fracture zones. The fracture densities were set to 3%, 2%, 7% and 4%, respectively. The Tracks 2 and 3 are the captured gamma counts of the near and far detectors before and after fracturing, respectively. In Track6, Sigma_cor can be obtained from Sigma0 by correction of neutron self-shielding effect. In track, the fracture density $\rho_0$ is calculated by Sigma0 and the fracture $\rho$ is calculated by Sigma_cor. It is very obvious that in the third fracturing layer, the fracture density is consistent with the model after correction.

Figure 5 The simulation example

Conclusions

A new enhanced calculation method utilizing PGNAA evaluating hydraulic fracturing in unconventional reservoirs is proposed in this paper. According to theoretical analysis and numerical simulation, a self-shielding factor calculation method was established by time spectrum and energy spectrum. And it is applied to the calculation of fracture density in hydraulic fracturing, which improves the accuracy of density calculation. The final simulation example also verifies the effectiveness of the method.

Acknowledgements

The authors would like to acknowledge the support of the National Natural Science Foundation of China(41974127,41574119), the National Science Technology and Major Special Fund of China(2017ZX05019005-005).

References

