**Introduction**

CO₂-EOR technology solves the problems of development of low permeability heavy oil reservoir and storage of CO₂, the distribution and migration of CO₂ in the formation is characterized by quantitative monitoring of CO₂ saturation. Generally, acoustic logging, temperature logging and micro seismic method can evaluate the formation before and after CO₂ injection. Due to the difference of neutron characteristic parameters (cross-section, density, hydrogen index and neutron moderation capacity, etc.) of formation water, heavy oil and CO₂, nuclear logging methods such as PNC and C/O are used to quantitative monitoring CO₂ saturation as well, and we used to quantitatively monitor the CO₂ saturation by the gamma count ratio difference of three detectors (Zhang et al. 2019).

Furthermore, we propose a method to evaluate the gas-bearing properties of reservoirs quantitatively by using the fast neutron elasticity parameter. However, the fast neutron elastic scattering cross section (FNXS) cannot be measured directly in the process of fast neutron deceleration. Based on the three-detector detection system, we use inelastic gamma and capture gamma information to characterize FNXS. After that, we proposed a model for quantitative monitoring CO₂ saturation. Monte Carlo method is used to simulate the response of FNXS with different porosity and CO₂ gas saturation. Particularly, the effect of formation pressure, temperature and borehole fluid is corrected. The effectiveness of this method can be demonstrated by simulation application. This study provides an effective method for monitoring CO₂ reserves in CO₂ gas drive reservoirs.

**Method and theory**

Fast neutrons will be slow down immediately after it occurs. In the first extremely short time interval, neutron inelastic scattering dominates the process, fast neutrons produce secondary inelastic gamma ray due to the interaction of fast neutron with elemental nuclei in the formation. After inelastic/elastic scattering deceleration, the fast neutrons slow down to thermal neutrons, capture gamma is released due to diffusion and capture. Three-detector detection system can characterize fast neutron cross sections indirectly by measuring inelastic and capture gamma information.

According to the fast neutron scattering theory, the fast neutron flux distribution where inelastic scattering occurs is:

\[ \phi_i(r) = \frac{S_{0}}{4\pi r^{2}} e^{-r/L_i} \]  

(1)

Fast neutron scattering theory shows that the secondary inelastic scattering gamma flux and capture flux in the formation can be expressed as follows:

\[ \phi_{s2}(R) = \frac{I_{\text{cap}}S_{0}}{4\pi R} e^{-R(1-\alpha)/(L_i \alpha \rho \mu)} \]  

(2)

\[ \phi_{\text{cap}}(R) = \frac{I_{\text{cap}}S_{0}}{4\pi R L_i^2(L_i^2 - L_f^2)} \int_0^\infty e^{-r/L_f} e^{-\rho \mu r^2} dr \]  

(3)

The mathematical relationship of the gamma count ratio and the fast-neutron moderation length is derived:

\[ R_{12} = \frac{N_1}{N_2} = \frac{R_{12}^2}{R_{12}^2} \int_0^\infty e^{-r/L_f} e^{-\rho \mu r^2} dr = \frac{R_{12}^2}{R_{12}^2} e^{-(R_{12} - R_{12})^2/L_f^2} \]  

(4)

It can be seen from the above equation that the inelastic gamma flux is not only related to FNXS, but also to other formation characteristic parameters. The capture gamma ratio is a function of the fast-neutron moderation length \(L_f\), where \(L_f\) is closely related to formation characteristic parameters. The combination of them can eliminate the influence of other characteristic parameters such as lithology and petroliferous property to characterize FNXS accurately.

Considering both inelastic and captured gamma information, a new parameter \(C\) obtained by three detectors information combination is introduced to reduce the influence of other formation parameters:

\[ C = \left[ \frac{N_{\text{cap}2}}{N_{\text{cap}1}} \right]^{1/2} \]  

(5)

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Where $N_{\text{in}}$ is the inelastic gamma count of the far detector, $N_{\text{cap1}}$ and $N_{\text{cap2}}$ are the capture gamma count of the near and far detectors.

According to the ENDF/B-VII.0 nuclear database analysis, Figure 1 shows the value of FNXS under different medium conditions.

Monte Carlo method was used for research and analysis, the instrument and formation model is shown in Figure 2. The borehole is filled with fresh water, 20cm diameter size, sandstone, limestone and dolomites as the formation matrix, stainless steel as the 0.7cm thickness casing, and CaSiO$_3$ as the 3cm thickness cement. The source distances of three detectors are 27.5cm, 40cm and 60cm.

Establish the relationship between parameter C and FNXS, there is a clear and strong correlation between them, shown in Figure 3:

$$\text{FNXS} = -5.13 \times C - 59.55 \quad (6)$$

Change the formation porosity from 0% to 40%, and the CO$_2$ gas saturation is set as 0% to 100%. Formation pore fluid exists under certain conditions (pressure 35MPa, temperature 373.15K). In such conditions, CO$_2$, water and heavy oil density is 0.5g/cm$^3$, 1.0g/cm$^3$ and 0.95g/cm$^3$, respectively. The response of FNXS to porosity under different CO$_2$ gas saturation is shown in Figure 4.

The CO$_2$ saturation interpretation model has been established, as shown in Figure 4. Based on the differences in FNXS under different gas saturations and formation porosity, the CO$_2$ saturation can be accurately obtained.
Influencing factors

The response analysis of complex wellbore-formation conditions was carried out. The response relationships are simulated and analysed for the formation shale content, methane content, formation pressure and temperature, and borehole environment, shown in Figure 5-9.

From the analysis of influencing factors, the CO₂ saturation interpretation model should be corrected due to the shale content in the formation. The presence of methane will have a slight impact on the saturation calculation, it is likely that the measurement result of CO₂ saturation is the total saturation of CO₂ and methane. The influence of formation temperature and pressure can be ignored when using FNXS to evaluate CO₂ saturation. And it is necessary to distinguish the type of borehole fluid and correct the gas-bearing.

Example

A simulation example shows the effectiveness of using fast neutron scattering cross-section to evaluate the gas saturation of CO₂ injection formation. The formation thickness is 107m, and separated by clay. The parameters of each reservoir are shown in Table 1. Except for the depth records, the original formation information is displayed in records 1, 2 and 3, the CO₂ saturation results and errors are displayed in records 5 and 6.

![Image](https://example.com/image1)

![Image](https://example.com/image2)

![Image](https://example.com/image3)

![Image](https://example.com/image4)

![Image](https://example.com/image5)

![Image](https://example.com/image6)

![Image](https://example.com/image7)

![Image](https://example.com/image8)

![Image](https://example.com/image9)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Matrix</th>
<th>Por/p.u.</th>
<th>Den /g.cm³</th>
<th>Vₛᵢ/%</th>
<th>Pore fluid composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Sandstone</td>
<td>30</td>
<td>2.114</td>
<td>10</td>
<td>CO₂20%+Sₜ80%+Sₜ50%</td>
</tr>
<tr>
<td>B</td>
<td>Sandstone</td>
<td>20</td>
<td>2.484</td>
<td>0</td>
<td>CO₂70%+Sₜ10%+Sₜ20%</td>
</tr>
<tr>
<td>C</td>
<td>Sandstone</td>
<td>35</td>
<td>1.9415</td>
<td>10</td>
<td>CO₂50%+Sₜ5%+Sₜ25%+SₜCH₄20%</td>
</tr>
<tr>
<td>D</td>
<td>Limestone</td>
<td>25</td>
<td>2.1825</td>
<td>0</td>
<td>CO₂50%+Sₜ50%</td>
</tr>
<tr>
<td>E</td>
<td>Sandstone</td>
<td>30</td>
<td>2.0466</td>
<td>50</td>
<td>CO₂70%+Sₜ30%</td>
</tr>
<tr>
<td>F</td>
<td>Sandstone</td>
<td>20</td>
<td>2.25</td>
<td>25</td>
<td>CO₂60%+Sₜ40%</td>
</tr>
</tbody>
</table>

Figure 10 shows the application results of CO₂ saturation measurement in heavy oil reservoirs with different lithology, porosity, shale content and pore fluid. For sandstone or limestone with heavy oil, the monitoring method of CO₂ saturation is effective, and the error is less than 6%. The ability of this method to identify CO₂ and CH₄ is relatively weak. When there is 20% CH₄ gas saturation in 35% porosity (C) sandstone formation, the error is about 13.5%, which is slightly smaller than the total gas saturation of CH₄ and CO₂. This phenomenon also confirms the conclusion that it is difficult to
distinguish gas types by this method, and the CH4 content should be strictly controlled during the gas drive construction.

Fig 10 The simulation example

Conclusions

A method of quantitative monitoring of gas saturation in CO₂ injection reservoir by FNXS is proposed. The CO₂ saturation interpretation model is established, and different influencing factors are analysed. The results show that when there is shale, methane in the formation or gas in the borehole, the correction of influencing factors should be carried out first. Finally, the effectiveness of quantitatively monitoring and evaluating CO₂ saturation using FNXS is verified by taking complex formation as an example.

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References


