Study on thermal cracking of mudstone induced by thermal recovery of heavy oil

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Abstract. Steam assisted gravity drainage (SAGD) is an effective thermal recovery method for heavy oil reservoirs. Mudstone interlayers with low-permeability may block the expansion of the steam chamber and then reduce the SAGD thermal recovery. However, the mudstone may be thermally fractured by the coupling effects of thermal-hydro-mechanical (THM) in the SAGD production process. In this study, taking a heavy oil reservoir in Xinjiang as an example, we studied the thermal cracks’ initiation of mudstone interlayer by numerical simulation. Results show that: (1) Temperature changes are the main factor of affecting mudstone’s fracturing or crack propagation, and the effects of mudstone interlayer's thickness are slightly. (2) With larger Young’s modulus, the critical fracturing temperature is lower. (3) In the peak period of gravity drainage, along the horizontal well, most of the mudstone interlayers reach the fracturing critical value and produce thermal cracks. The existence of thermal cracks will improve the SAGD productivity.

1. Introduction

Heavy oil is playing significant role in oil and gas development[1]. Due to the sedimentary environment and the hydrodynamic changes, the spatial distribution of heavy oil reservoirs is often heterogeneous, which may affect the expansion of the steam chamber of the SAGD process and bring challenges to horizontal well heavy oil recovery.

Through experiments and numerical simulation, researchers have presented some models including the size, dimensional positions, and physical properties of mudstone interlayer to evaluate its impact on SAGD development quantitatively. Yang and Butler[2] added shale interlayer with changes of permeability and size to study the influence of interlayer on SAGD development. Some other researchers[3] numerical simulated the interlayer's parameters (location, thickness, density, and distribution) effects on the SAGD development. Furthermore, through the optimization of SAGD parameters, we could control the mudstone interlayer's cracking propagation or mudstone thermal fracturing process, and then reduce the interlayer’s impact on productivity.

About SAGD field production or technology, the engineers have been trying to reduce the flow resistance of heavy oil in the interbedded reservoir. Zhou et al.[4] believed that increasing injection pressure can enhance driving power during the steam through mudstone interlayer. Saeedi et al.[5] further studied the feasibility of multi-stage fracturing to improve the application effect of SAGD technology, but they didn't carry out field experiments limited by conditions.
In this study, based on the field data of heavy oil reservoir in Xinjiang, we build a geo mechanical model to study the mudstone interlayers distribution, stress setting, SAGD production parameters, thermal properties of mudstone by CMG reservoir numerical simulation software and FEPG finite element software.

2. Numerical Model

2.1 Geometric Model

This study takes a reservoir in Haqian 1 area of Chunhui oilfield in Xinjiang as the target case. The lithological characters are mainly gray or grayish-brown medium-fine sandstone, conglomeratic sand, and medium-fine conglomerate. There are mudstone interlayers in the oil reservoir, which are mainly distributed at a depth of about 310 m. During the SAGD pilot test, researchers found that the development was not ideal because the mudstone interlayers obstructed the steam chamber's expansion. Using CMG and FEPG, we establish the mudstone interlayer's thermal-deformation coupling numerical model, as shown in Figure 1. Along the xyz directions of the coordinate axis, the size of the model is 110 m × 500 m × 25 m, the size of the grid element is 10 m × 20 m × 1 m, and the number of grids is 11 × 25 × 25.

![Figure 1. 3D model of reservoir numerical simulation](image)

The CMG numerical model's reservoir basic parameters are in Table 1, and the rock mechanical parameters of the reservoir and mudstone interlayer are in Table 2.

| Parameters                  | Value          | Parameters                  | Value          |
|-----------------------------|----------------|-----------------------------|----------------|
| Oil-bearing area (km²)      | 0.055          | Mean permeability (μm²)     | 780×10⁻³       |
| Reservoir top depth (m)     | 300            | Crude oil density (g/cm³)   | 0.9836         |
| Effective thickness (m)     | 25             | Permeability ratio k_v/k_h  | 0.77           |
| Well group spacing (m)      | 110            | porosity                   | 29.3%          |
| Geological reserves (t)     | 25.36×10⁴      | Initial oil saturation     | 0.64           |
| Crude oil viscosity (mPa·s) | 500×10⁴        | Initial pressure (MPa)      | 3.2            |
| Reservoir temperature (℃)   | 23             |                             |                |

| Parameters                  | Reservoir     | Mudstone interlayer         |
|-----------------------------|---------------|-----------------------------|
| Young’s modulus E (GPa)     | 6.5           | 10~13                       |
| Poisson’s ratio ν (-)       | 0.25          | 0.23                        |
| Tensile Strength σ_y (MPa) | 1.5           | 1.2                         |
| Internal friction angle φ (°) | 35           | 32                          |
| Cohesion C (MPa)            | 5.0           | 2.5                         |
2.2 Numerical simulation process
Firstly, the SAGD thermal recovery reservoir is simulated by CMG. Secondly, the node grid temperature field and pressure field obtained by numerical simulation are derived and be input into FEPG for analysis to judge the generation and distribution of mudstone cracking induced by thermal recovery.

2.3 Mudstone cracking criterion
According to reference [6], the in-situ stress due to self-weight is determined by the following formulas:

\[
\begin{align*}
\sigma_z &= \sigma_v = \int_0^z \rho(z)\,dz \\
\sigma_{x1} &= \frac{\nu}{1-\nu}(\sigma_v - \alpha p_p) + \alpha p_p \\
\sigma_{y1} &= \frac{\nu}{1-\nu}(\sigma_v - \alpha p_p) + \alpha p_p
\end{align*}
\]

where \(\sigma_v\) is the vertical geo-stress, \(\rho(z)\) is the overburden density, \(\sigma_{x1}\) and \(\sigma_{y1}\) are the horizontal geo-stresses, \(\nu\) is the Poisson's ratio, \(p_p\) is the pore pressure and \(\alpha\) is the effective stress coefficient.

During SAGD thermal recovery, the thermal expansion stress is determined by the formula (2):

\[
\begin{align*}
\sigma_{x2} &= 2G \frac{1+\nu}{1-2\nu} \alpha^T(T - T_0) \\
\sigma_{y2} &= 2G \frac{1+\nu}{1-2\nu} \alpha^T(T - T_0)
\end{align*}
\]

where \(\alpha^T\) is the coefficient of thermal expansion, \(G\) is the shear modulus, \(T_0\) is the initial temperature of the reservoir, \(T\) is the reservoir temperature after heating, and \(\sigma_{x2}, \sigma_{y2}\) are the additional in-situ stresses caused by the temperature rise in the horizontal direction.

Therefore, the total geo-stress formulas of the formation are as follows:

\[
\begin{align*}
\sigma_z &= \sigma_v = \int_0^z \rho(z)\,dz \\
\sigma_{H} &= \sigma_{x1} + \sigma_{x2} \\
\sigma_{h} &= \sigma_{y1} + \sigma_{y2}
\end{align*}
\]

To determine the cracking of mudstone, we define the cracking parameter \(K\), and when \(K \geq 0\), mudstone will crack.

When a certain point's stress in the mudstone is greater than the rock tensile strength, the mudstone will produce a tensile cracking. Therefore, the tensile cracking parameter \(K_t\) can be defined as:

\[
K_t = \sigma - \sigma_t
\]

where \(\sigma_t\) is the mudstone’s tensile strength.

The Drucker-Prager strength criterion is introduced when the mudstone shear cracking occurs[7], and the shear cracking parameter \(K_s\) is defined as:

\[
K_s = \alpha_p l_1 + \sqrt{j_2 - k}
\]
where \( I_1 \) is the first invariant of the stress tensor, \( J_2 \) is the second invariant of the stress deflection,
\[
\alpha_0 = \frac{2 \sin \varphi}{\sqrt{3(3 + \sin \varphi)}}, \quad k = \frac{6 \cos \varphi}{\sqrt{3(3 + \sin \varphi)}} C, \quad \varphi \text{ is the internal friction angle of rock, } C \text{ is the cohesion.}
\]

3. Results and Discussion

3.1. Reservoir stress distribution

To study the mudstone interlayer's stress state under the temperature, change more directly, the local heat source is applied to the mudstone interlayer in the center of the section to simulate the reservoir model. The thickness of the mudstone interlayer is 1.0 m, and the permeability is \( 0.001 \times 10^{-3} \text{ um}^2 \).

Figure 2 shows the stress distribution and the corresponding cracking parameters (K) when the mudstone interlayer's elastic modulus is 13 GPa under different heat source temperatures.

![Figure 2. Cracking parameter value under different heat source temperatures](image)

It can be seen from Figure 2 that the mudstone interlayer's stress at the heat source is the highest, and the stresses submit to gradient characteristics along with the horizontal and vertical directions obviously. With the increase of the temperature, the local stress near the heat source increases gradually, and the cracking parameters of the mudstone interlayer also increase continuously. Once the stress reaches the tensile cracking or shear cracking condition, the mudstone interlayer will crack.

Comparing the cracking parameters under different heat source temperatures, we can find that when the temperature is 100 °C, 200 °C, and 250 °C, the cracking parameter is less than zero, which indicates that the mudstone interlayer has not cracked. However, the cracking parameters gradually increase with the increase of temperature. When the temperature rises to 300 °C, the cracking parameter value is 0.431 > 0, so the mudstone interlayer has cracked according to the mudstone fracture criterion.

3.2. Factors and temperature conditions of mudstone interlayer cracking

To study the influence of mudstone interlayer thickness on thermal cracking, we select three interlayer thickness (0.5 m, 1.0 m, and 1.5 m) to analyze and compare. Figure 3 shows the stress distributions under different interlayer thickness when the heat source temperature is 200 °C and 300 °C. Table 3 shows the cracking parameters of different interlayer thickness under different heat source temperatures.

| Temperature | Thickness=0.5 m | Thickness=1.0 m | Thickness=1.5 m |
|-------------|----------------|----------------|----------------|
| T=200 °C    | -0.9           | -0.899         | -0.899         |
| T=300 °C    | 0.458          | 0.431          | 0.41           |

Table 3. Cracking parameters under different heat source temperatures.
Figure 3. Stress distributions under different heat source temperatures

It can be found from Figure 3 and Table 3, under the same heat source temperature, even if the thickness of the mudstone interlayer is different, the reservoir's stress state, the mudstone interlayer's stress state, and the values of mudstone cracking parameters are very similar. We can conclude that the temperature is the main factor affecting the stress distribution and cracking of mudstone, while the interlayer thickness has a small influence.

From the above analysis, we can conclude that the temperature is the main factor leading to mudstone cracking in thermal recovery. It is crucial to determine the critical temperature of mudstone cracking for understanding the thermal cracking condition of mudstone. Taking the mudstone interlayer's elastic modulus as 10 GPa and 13 GPa as cases, we studied the variation of cracking parameter with temperature and determined the critical fracture temperature. Figure 4 shows the variation curve of cracking parameters of mudstone interlayer with temperature.

Figure 4. Variation curve of cracking parameters of mudstone interlayer with temperature

It can be seen from Figure 4 that the cracking parameters of mudstone increase with the increase of temperature. According to the cracking criterion, the temperature corresponding to $K=0$ is the critical temperature of mudstone cracking. According to the calculation, the critical cracking temperature of mudstone with the elastic modulus of 10 GPa is 271.88 °C, elastic modulus of 13 GPa is 265.43 °C, respectively, and the higher the elastic modulus of mudstone, the lower the critical cracking temperature. The reasons are as follows: The main factor that affects the cracking of mudstone is temperature. The
larger elastic modulus will produce higher temperature stress with the same temperature variation, which will lead to the mudstone cracking easier.

3.3. The distribution range of mudstone interlayer cracking in SAGD development

To study the fracture of mudstone along horizontal well in different periods of SAGD thermal recovery, we analyzed two cases (the end of the cycle preheating and the peak period of production oil drainage).

In the cyclic pre-heating stage, steam is injected simultaneously into both horizontal wells. The steam temperature is 300 °C, the injection rate is 160 m³/d, the dryness fraction of steam is 0.7, and the cyclic pre-heating period is 7 months. During the SAGD production period, the upper horizontal well injects steam, the lower well produces oil. The injection steam temperature is 270 °C, the steam injection rate is 100 m³/d, the liquid production rate is 120 m³/d, and the steam dryness fraction is 0.8. The elastic modulus of mudstone is 13 GPa.

Figure 5 shows the cracking distribution of the mudstone interlayer along the horizontal wellbore at the end of the cyclic pre-heating and the peak period of oil drainage (18 years of simulated development).

![Figure 5. Distribution curve of mudstone cracking parameters along the horizontal wellbore](image)

It can be seen from figure 5 that at the cyclic preheating end, except the local area near the steam injection heel point, others along the horizontal well do not reach the mudstone cracking conditions, so the mudstone interlayers do not occur cracking. This is mainly because the overall temperature of the reservoir is not high at this time. In the gravity drainage peak, the mudstone interlayers' cracking parameters are higher than zero in most areas along the wellbore. This means that the mudstones have reached the cracking condition and have occurred cracking. The existence of thermal cracking is conducive to the migration of steam and heavy oil in the reservoir, thus to improve the SAGD development effect of mudstone interlayered reservoir.

4. Conclusions

Taking a shallow heavy oil reservoir in Xinjiang as a case, we studied the stress distribution, cracking condition, and cracking distribution range of mudstone interlayer under the coupling of thermal-deformation. The following conclusions can be obtained:

(1) The temperature is the main factor affecting the stress distribution and cracking of mudstone, while the interlayer thickness has a small influence.

(2) The critical cracking temperature of mudstone with the elastic modulus of 10 GPa is 271.88 °C, elastic modulus of 13 GPa is 265.43 °C, respectively, and the higher the elastic modulus of mudstone, the lower the critical cracking temperature.

(3) In the gravity drainage peak, the mudstone interlayers in most areas along the wellbore have reached the cracking condition and have occurred cracking. The existence of thermal cracking is
conducive to the migration of steam and heavy oil in the reservoir, thus to improve the SAGD development effect of mudstone interlayered reservoir.

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