Numerical Analysis of Casing Damage in Heavy Oil Thermal Recovery Wells

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Abstract. With the decrease in the world's thin oil resources, heavy oil resources gradually become the main resources in the current and coming period. However, the casing damage of thermal recovery wells seriously restricts the development and exploitation of heavy oil. By investigating geological conditions, production status, and casing damage from in Liaohe Oilfield, the mechanism of casing damage in heavy oil thermal recovery wells was analyzed. Through establishing a casing-cement sheath-formation model and using a thermosetting coupling model of transient heat transfer, the temperature field and stress field of casing in the perforation section were simulated and studied, and the influence law of thermal stress generated by high temperature on the casing was analyzed. The damage of perforated casing is mainly caused by thermal stress, making the casing bear the alternating load of high temperature and high pressure, research shows. After multiple rounds of steam huff and puff, the residual stress of casing increases with the period, resulting in casing fatigue failure. Meanwhile, sand production seriously abrades casing, causing stress concentration of casing and then accelerating casing damage. By studying the casing optimization design, the occurrence of casing damage in heavy oil thermal recovery wells can be reduced and even prevented.

1. Introduction
At present, there are serious casing damage problems in many thermal recovery wells of heavy oil fields, and the main types of casing damage are shrinkage, rupture, dislocation, and corrosion [1]. Under the actual wellbore conditions of heavy oil thermal recovery wells, the temperature field of the wellbore and the formation has changed greatly due to the injection of high-temperature hot steam. As a result, the stress distribution and the stress field of the casing were changed, and the casing was subjected to the compression load generated by the thermal stress and the alternating load generated in the process of steam stimulation. The harsh stress conditions and temperature conditions made the casing lower in strength or even be damaged at high temperatures. The problem of casing damage has brought great troubles to the production of heavy oil fields and has severely restricted the development of heavy oil production. L J Han and J H Jia [2] proposed a strain-based thermal well casing design method. The finite element software was used to establish a three-dimensional elastoplastic model to simulate and analyze the interaction between the stress field and the strain changes during the gas injection production process of the thermal well. X F Yu, H L Zheng, etc. [3] established that the high-temperature non-uniform stress caused the casing to bear thermal stress and non-uniform load, which caused the casing to fail. Considering the change of the casing yield strength and elastic modulus during the steam injection production process, the tubing, the finite element model of the casing,
cement ring, and formation coupling system respectively studied the influence of steam injection temperature, steam injection pressure, and steam injection speed on casing deformation and failure. Bour and D L \cite{4} studied the casing damage caused by cement ring damage in cyclic steam injection production and put forward new preventive measures. Rashid Al Shaibi and Mukhaizna \cite{5} studied the casing damage mechanism through finite element software considering the coupling of formation. S Franks, J Wise \cite{6} researched casing damage caused by sand production in thermal recovery wells and successfully implemented resin-injected sand control measures in the North American Cohen River Oilfield to prevent casing damage in thermal recovery wells. Chris Carpenter \cite{7} established a model for thermal recovery wells and analyzed the stress conditions of thermal recovery well strings. With full consideration of the mechanical complexity of the formation, a general engineering design method was proposed for thermal recovery well strings.

For the time being, in terms of casing damage mechanism for thermal recovery wells of heavy oil, the causes of casing damage are mainly analyzed qualitatively, but not quantitatively \cite{8}. According to the field conditions of Liaohe oilfield, the ANSYS model was established for numerical simulation, and the wellbore temperature field was simulated with the field data and coupled with the stress field. The factors affecting the casing damage were studied by analyzing the actual stress conditions of the casing in the thermal recovery wells of heavy oil. By analyzing the mechanism of casing damage in thermal recovery wells of heavy oil, the casing was optimized, and effective preventive measures were taken to provide a theoretical basis for reducing and preventing casing damage.

2. Temperature field simulation and casing damage analysis
Steam flooding and steam stimulation are generally considered as a thermal recovery process, and steam flooding is regarded as a cycle of steam stimulation. There are three main processes of steam stimulation: steam injection stage, well-simmering stage, and oil recovery stage \cite{9}. The duration of the steam injection phase is about 15 days, and the high-temperature saturated steam is continuously injected into the tubing, so the heat of the wellbore continues to rise; the good injection phase stops the steam injection into the wellbore, and the duration is about 5 days. The heat of the high-temperature wellbore is transferred to the formation and its heat keeps decreasing; the heat change in the wellbore during the oil recovery phase is very small, so it is considered that the wellbore temperature and the formation temperature are equivalent during the oil recovery phase, and no heat exchange occurs. Therefore, analysis of heavy oil thermal recovery wells only requires analysis of the temperature field when the wellbore reaches a quasi-steady state during the steam injection phase.

2.1. Basic Assumptions
Making the following assumptions about the simulation conditions of temperature field: 1. Tubing, casing, cement ring coaxial; 2. The cementing quality is good, and the cement ring is tightly connected with the formation and forms a combined elastomer; 3. The whole well section is composed of a single casing with uniform thickness. Besides, the casing and cement are tightly connected to the cement ring and formation without slipping each other; 4. The inlet of the simulated well section is the same as the surface wellhead steam injection parameters, etc.; 5. Steam injection does not affect the original in-situ stress; 6. The injected wet steam has stable flow characteristics, and the heat transfer along the good diameter is one-dimensional radial steady-state heat transfer; 7. When considering the influence of steam injection temperature and other factors on the oil layer casing separately, it is assumed that there is no heat loss in the longitudinal direction of steam; 8. When considering the thermal insulation performance of the packer, the apparent thermal conductivity of the high-temperature packer is set very small, similar to the thermal conductivity of the thermal insulation tube; 9. When simulating the wellbore temperature field at a certain temperature, it is necessary to consider the temperature field distribution when the wellbore reaches a quasi-steady state.

2.2. Modelling
Using the finite element software ANSYS for numerical simulation. The depth of the modeled well was set to 800m, and the position of the lower packer was 700m. The simulation used the structure of the most commonly used thermally insulated tubing steam injection pipe string in the Liaohe thermal
recovery well. The apparent thermal conductivity of the packer was adjusted to be very low (approximately regarded as an insulated object). According to the geothermal statistics of Du 84 block in Liaohe Oilfield, the formation temperature at the depth of 800m was 51.4 °C, and the temperature at the depth of the packer around 700m was about 48.1 °C. The diffusion of temperature in the formation was generally near the wellbore zone, so the model radius was 10m, and the model of thermal insulation tubing-annulus-casing-cement ring-formation was established \[^{10}\]. In this temperature field simulation, insulated tubing, annulus, and high-temperature packers were added, and the casing-cement ring-formation system at the upper and lower sections of the 700m downhole packer was taken as the research object. Considering the symmetry of the model, a quarter model was selected for analysis, and the axisymmetric model shown in figure 1 below was established. The specific parameters of materials are shown in table 1 and table 2.

![Axisymmetric model of thermal production wellbore.](image)

**Figure 1.** Axisymmetric model of thermal production wellbore.

**Table 1.** The specific parameters of materials.

| Materials          | Density kg/m³ | Thermal Conductivity W/m°C | Elastic Modulus GPa | Poisson's ratio | Linear expansion coefficient 10⁻⁶°C⁻¹ |
|--------------------|---------------|----------------------------|---------------------|-----------------|-------------------------------------|
| Tubing Insulated pipe | 7850          | 56.5000                    | 56.87              | 2.05            | 0.30                               |
| Annulus            | 1             | 0.0060                     | 0.3465             | 0.29            | 12.0                               |
| Casing             | 7850          | 43.2700                    | 43.87              | 0.24            | 13.0                               |
| Cement             | 2650          | 0.3000                     | 0.3465             | 0.15            | 10.3                               |
| Stratum            | 2390          | 1.6870                     | 1.75               | 0.23            | 10.5                               |

**Table 2.** Elastic modulus and yield strength of casing at different temperatures.

| Temperatures/°C | Elastic Modulus/GPa | Yield limit/MPa |
|-----------------|---------------------|------------------|
| 150             | 210                 | 716.37           |
| 200             | 175                 | 716.37           |
| 250             | 163                 | 708.88           |
| 280             | 147                 | 684.38           |
| 300             | 120                 | 657.31           |
| 350             | 115                 | 640.78           |

2.3. Analog computation of temperature field

The temperature field analysis model was established to simulate the thermal insulation pipe-annulus-casing-cement ring-formation model established as shown in figure 2.
In the finite element simulation of radial heat dissipation in the wellbore, it was found that changing the steam temperature has little effect on the radial diffusion of temperature. Figures 3 to 6 simulate the temperature diffusion of the wellbore injected with steam at 346 °C into the casing of the reservoir below the packer 700m underground. It can be seen from the cloud diagram of temperature diffusion that as the steam injection time increases, the steam in the wellbore continuously heats the wellbore, and the temperature diffuses radially along with the formation. At the beginning of steam injection, 346 °C steam heated the wellbore, but it had almost no effect on the formation temperature. With the increase of steam injection time, the heat is continuously transferred along the radial direction of the wellbore-tubing-oil casing annulus-casing-cement ring-formation, and the influence range gradually increases. However, the temperature diffusion during steam injection is limited to the near-wellbore...
zone, that is, within the range of 10m outside the wellbore, and the formation temperature more than 10m away from the wellbore, the influence of steam injection on it can be ignored. The temperature fields studied below are all when the wellbore reaches a quasi-steady state.

2.5. Effect on the temperature of the perforating casing
Because the casing of the perforated section is exposed to high temperature, the temperature of the inner wall of the casing is the same as the steam injection temperature, so this simulation applies a temperature value of 346°C to the inner wall of the casing to simulate the temperature distribution of the casing. The results are shown in figure 7.

![Figure 7. Casing temperature distribution.](image1)

![Figure 8. Partially enlarged cloud image.](image2)

It can be seen from the above figure 8 that the temperature distribution of the casing can be seen by partially enlarging the cloud image. The minimum temperature is 202.38 °C and the maximum is 346 °C on the inner wall of the casing. By selecting a series of nodes on the outer wall of the casing and calculating the resulting temperature value, observe the temperature distribution of the outer wall of the casing. The results are shown in figure 9.

![Figure 9. Distribution diagram of casing wall temperature.](image3)

Through calculation, it was found that the temperature of the outer wall of the casing was high, and the temperature was about 150 °C. Due to the long-term exposure of the casing to a high-temperature environment, the casing was prone to thermal deformation, expansion, and fatigue damage, reducing the service life of the casing and causing casing damage.

3. Simulation calculation of stress field and analysis of casing damage
In heavy oil thermal recovery wells, due to the injection of high-temperature hot steam, the internal temperature of the casing is too high, but the casing is constrained by the cement ring and formation, so the casing is subjected to the compressive load caused by thermal stress \(^{(1)}\). According to rock mechanics and elastoplastic theory, the thermal-structure coupling mechanics problem in three-dimensional space is reduced to a plane symmetry strain mechanics problem. The temperature field
simulated using ANSYS considers the condition of the insulated pipe, and the mechanical model of casing-cement ring-stratum is used for analysis under the coupled stress field. The corresponding stress field can be calculated by substituting the solution result of the temperature field as the body load into the stress field model.

3.1. Physical model of the stress field
The established stress field model is shown in figure 10. Similar to the temperature field model, 1/4 of the wellbore is also selected for stress field analysis. Due to the inelastic modulus and other parameters of the annulus, the temperature field and the stress field are coupled to each other.

![Finite element model mesh and local finite element mesh.](image)

**Figure 10.** Finite element model mesh and local finite element mesh.

3.2. Finite element simulation of the stress field
The total deformation cloud diagram of the casing was obtained through simulation calculation. At this time, the effect of the in-situ stress on the casing was not considered, and only the influence of the casing on the casing itself under the complex action of underground high temperature and high pressure was considered. It can be seen from figure 11 that the maximum deformation of the casing is serious, causing damage to the casing body, reducing the service life of the casing, and causing damage to the casing.

![Total deformation cloud image of the casing.](image)

**Figure 11.** Total deformation cloud image of the casing.

The figure below calculated the shear stress value of the casing. From the figure 12, the minimum value is -317.85MPa and the maximum value is 282.91MPa. The stressed environment of the casing is complex, which is easy to cause fatigue damage to the casing and accelerate casing damage.

![Cloud diagram of casing shear stress.](image)

**Figure 12.** Cloud diagram of casing shear stress.

![Cloud diagram of sleeve Mises stress.](image)

**Figure 13.** Cloud diagram of sleeve Mises stress.
The Mises stress cloud diagram of the casing was obtained through calculation, and a series of nodes were selected to obtain the specific Mises stress value of the casing. It can be seen from figure 13 that part of the casing has exceeded the yield limit of the casing. The casing is in the yield state. Under long-term high-temperature conditions, it will cause irreversible strain on the casing and accelerate casing damage.

By selecting the nodes as shown in figure 14, it can be seen that the casing is under complex stress and is in a non-uniform stress environment. In the long-term situation, the casing is prone to fatigue and deformed under stress.

Figure 15 is a partially enlarged cloud image of the Mises stress of the casing. It can be seen that the minimum value is 513.99MPa and the maximum value is 685.8MPa, which is close to the yield strength of the casing, which is easy to cause fatigue damage to the casing and reduce the service life of the casing.

3.3. Casing fatigue analysis

The life of the casing was calculated by fatigue analysis with a cycle of 20 days, and the calculation results are shown in figure 16 and figure 17.
Figure 18 above shows the results of fatigue sensitivity with a minimum base load change of 50% and a maximum base load change of 200%.

3.4. Calculation of casing residual stress
The heat production method of steam stimulation mainly includes three stages: steam injection stage, soaking stage, and oil production stage. From the analysis of casing damage data, it can be seen that casing damage gradually increases seriously with the cycle of steam stimulation. After multiple rounds of steam huff and puff, the performance of the thermal insulation pipe decreases to a certain extent, which leads to casing damage, but more importantly, the residual stress generated on the casing after multiple rounds of steam huff and puff \[12\]. Since the casing is in the state of compression yield in a single period, under the premise that the unidirectional accumulation effect and Bauschinger effect are taken into account in the St. Canaan model, after every time the casing is in the state of yield, it cannot recover to the original stress state, and a part of residual stress will be generated in the casing. After each cycle of steam stimulation, the residual stress on the casing will increase. The casing can be damaged when the residual stress accumulates to a certain extent. In this paper, the casing stress of multi-cycle steam stimulation is numerically simulated, and a curve of casing stress with the steam injection cycle is obtained as shown in figure 19 below.

This time, the simulation of the casing stress variation during the 6-cycle throughput process was carried out. It can be seen from the figure that the casing has reached the yield limit of the casing under the initial steam injection of 346°C and produced a certain compressive yield. After the steam injection was removed during the simmering stage, the temperature in the wellbore proceeded to the formation conduction, the casing temperature continues to drop, and the Mises stress of 84MPa does not return to the original stress state after the end of the first cycle of 20 days. As the residual stress
value on the casing increases with each cycle, the residual stress value at the end of the sixth cycle is 196 MPa. Under such periodic steam throughput operations, the residual stress of the casing will continue to increase with the end of the cycles until the casing is destroyed.

4. Conclusion
The casing damage of heavy oil thermal recovery wells is the result of the combined action of various factors. The research found that it mainly includes the following aspects:

- The role of thermal stress
  The first and most important factor of casing damage in thermal recovery wells for heavy oil is that the casing is at a high temperature for a long time, which reduces the yield strength of the casing. The casing generates huge thermal stress and the external extrusion stress, internal pressure stress, and axial stress combined to form the stress field. The casing is subjected to the alternating load of thermal stress for a long time, and it undergoes multiple throughput rounds, resulting in fatigue failure.

- The impact of perforation
  Because casing damage depth is near the perforation section, the perforation reduces the original strength of casing, and the sand production of the oil layer around the perforation is easy to form holes, causing cement annulus cavity and accelerating cement annulus damage, aggravating casing stress concentration and increasing casing damage probability.

- Sand production
  Sand production in the oil layer is the result of long-term exploitation. The cavity caused by sanding in the oil layer makes the stress concentration in a part of the casing, which greatly increases the external squeeze stress on the casing. Due to the combined action of external squeezing force and thermal stress, the casing is deformed and destroyed. At the same time, the sand production severely abraded the casing and accelerated the casing damage.

- The influence of residual stress
  After multiple rounds of steam throughput, the casing produces residual stress. Since the casing is in a compressive yield state in a single cycle, each time the casing is yielding, it cannot be restored to the original stress state, and a part of residual stress will be generated in the casing. However, after multiple rounds of steam throughput, the residual stress on the casing will increase after the completion of each round of the throughput cycles. After the residual stress accumulates to a certain degree, the casing will be damaged. Under such periodic steam throughput operations, the residual stress of the casing will continue to increase with the end of the cycles until the casing is destroyed.

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