Study on Influence of temperature on cementing in deep shale oil and gas exploitation

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Abstract. In this paper, the mechanical model of sheath has been established according to the engineering practice and analysed in two aspects: temperature acts alone and temperature and pressure act together. The results demonstrate that it is unnecessary to worry the negative influence of individual temperature action. Temperature can cause many adverse characteristics temperature on cementing: thermal stress and material properties. The coefficient $\beta$ coming from the effective conduction of heat, prove the adverse condition of temperature on cement ring in terms of stress, and its size is positively correlated with temperature difference. Mechanical properties usually will be changed at high temperature, it can be measured by the later experiments, which can discuss the role of temperature is further.

1. Introduction
Wellbore integrity is the essential problems in the development of unconventional oil and gas energy. In the process of cementing, the cement is poured into the space between casing and formation, and it eventually forms a sheath with certain cementation ability under the complex borehole environment. The sheath has the function of effectively sealing and supporting formation. When large-scale staged fracturing technology is used for the exploration, engineers will carry out water injection, fracturing, acidizing, hole filling, other downhole operations. Different operation procedures will inevitably cause periodic changes in temperature stress and properties of the cement, which will often change the stress of sheath. It may lead to cracks in the sheath, or even failure of the sealing.

Different operation procedures will inevitably cause periodic changes in temperature stress and properties of the cement, which will often change the stress state of sheath. It may lead to cracks in the sheath, or even failure of the sealing. In recent years, many scholars have studied the integrity of cement. With the successful development of shale gas around the world, the failure of cement sheath in the production process has become a concern [1]. Wang and Taleghani noted that periodic changes of fluid pressure and temperature in the casing can lead to failure of the cement sheath [2]. The influence of nano-silica (NS) at different dispersion temperatures on the properties has been charfied [3]. In this paper, the maximum safe load under cyclic loading considering temperature is obtained through shakedown theory to guide engineering practice.

From the discussion above, it can be seen that the predecessors have insufficient understanding of cement damage under periodic load and high temperature cycles especially the mechanical mechanism analysis. In this paper, the maximum safe load under cyclic loading considering temperature is obtained through shakedown theory to guide engineering practice.
2. **Basic mechanical model and hypothesis**

As shown in Figure 1, the cement sheath is regarded as an annular structure made of cement. The size is generally fixed in engineering. The sheath’s inner diameter and outer diameter (139.7 mm and 233.5 mm) are usually in specification. In mechanics, cement sheath can be regarded as thick walled cylinder according to its internal and external diameter ratio. Secondly the wellhole cement shows very strong plasticity in material properties at high temperature [4]. Therefore, the mechanical model of cement sheath can be constructed by the following assumptions:

![Figure 1. Mechanical model](image)

1. The sheath is isotropic, and the mechanical equations in all directions are the same.
2. Cement elastic-plastic materials under high temperature and high pressure.
3. The cementing is satisfactory before bearing the periodic pressure damage.
4. Sheath yield follows Mohr-Coulomb yield criterion.
5. The internal temperature of casing will change periodically due to hydraulic fracturing.

3. **Analysis Theory**

Shakedown analysis usually used in structural analysis in civil engineering. Under the action of alternating load, the structure often has two states: stable state or deformation damage (ratchet effect or low cycle fatigue). Through the shakedown theory, we can determine a load range to keep the structure stable under periodic load. The Melan’s theorem as one of shakedown methods can be utilized to get the load range [5].

The direct construction residual stress method [6] can be applied to obtain the self-equilibrium stress field, which is the key to the use of shakedown theory. Obviously, due to the symmetry of the geometry of the sheath, the analytical solution can be calculated relatively easily. The advantage of stability theory is to bypass the loading history and directly get the safe loading in spite of other stress.

4. **Theoretical Solution**

When fracturing is not performed, there are only temperature changes caused by other processes. It is assumed that the sheath’s original temperature is $T_b$, which is the same as that of the stratum. After the start of operation, the temperature inside the casing decreased to $T_a$ due to heat exchange. The temperature outside is fixed. The temperature difference $\Delta T = T_b - T_a$.

When fracturing, the cement undergoes the repetitive force. The outside of the sheath undergoes pressure $P_0$, (MPa), because of the geo stress.
When $P_i$ and $T_a$ are not huge, the extra stress caused by them is small, the structure is elastic, and its stress distribution is

$$
\begin{align*}
\sigma_r &= \frac{m^2}{1-m^2} \left(1 - \frac{b^2}{r^2}\right) P_i - \frac{1}{1-m^2} \left(1 - \frac{a^2}{r^2}\right) P_0 + \kappa \left[ \frac{m^2}{1-m^2} \left(\frac{b^2}{r^2} - 1\right) \ln \frac{m}{r} - \ln \frac{b}{r} \right] \\
\sigma_\theta &= \frac{m^2}{1-m^2} \left(1 + \frac{b^2}{r^2}\right) P_i - \frac{1}{1-m^2} \left(1 + \frac{a^2}{r^2}\right) P_0 - \kappa \left[ \frac{m^2}{1-m^2} \left(\frac{b^2}{r^2} + 1\right) \ln \frac{m}{r} + \ln \frac{b}{r} - 1 \right]
\end{align*}
$$

(1)

Where, $a$ and $b$ are the dimension information, as shown in the Figure 1. $m=a/b$. And $\kappa$ is the temperature limit of the sheath.

When they vary, formula (1) will meet yield condition (2).

$$
\sigma_r = \sigma_0 t g^2 \left(45^\circ + \frac{\phi}{2}\right) - 2c t g \left(45^\circ + \frac{\phi}{2}\right)
$$

(2)

$c$ is cohesion force (MPa) and $\phi$ is internal friction angle (°).

$$
\frac{d\sigma_r}{dc} + \frac{1}{r} (\sigma_r - \sigma_\theta) = 0
$$

(3)

According to the Equilibrium condition (3), we can get

$$
\begin{align*}
\sigma_{\rho r} &= -\left( p + \frac{B}{1-K} \right) \left( \frac{r}{a} \right)^{1-K} + \frac{B}{1-K} + \frac{1}{2} \frac{km^2}{1-m^2} \left( \frac{1}{a^4} - \frac{1}{r^4} \right) + \kappa \ln \frac{a}{r} \\
\sigma_{\rho \theta} &= -\frac{1}{K} \left( p + \frac{B}{1-K} \right) \left( \frac{r}{a} \right)^{1-K} + \frac{B}{1-K} + \frac{1}{2} \frac{km^2}{K(1-m^2)} \left( \frac{1}{a^4} - \frac{1}{r^4} \right) + \kappa \ln \frac{a}{r} - \frac{B}{\kappa}
\end{align*}
$$

(4)

let

$$
K = t g^2 \left(45^\circ + \frac{\phi}{2}\right), B = -2ctg \left(45^\circ + \frac{\phi}{2}\right)
$$

(5)

The fracturing pressure $p$ (MPa) can be calculated according to (4),

$$
P_{\rho} = \left( p + \frac{B}{1-K} \right) \left( \frac{\rho}{a} \right)^{1-K} - \frac{B}{1-K} - \frac{1}{2} \frac{km^2}{1-m^2} \left( \frac{1}{a^4} - \frac{1}{\rho^4} \right) - \kappa ln \frac{a}{\rho}
$$

(6)

The stress in the elastic part can be calculated,

$$
\begin{align*}
\sigma_{r e} &= \frac{M^2}{1-M^2} \left(1 - \frac{b^2}{r^2}\right) P_i - \frac{1}{1-M^2} \left(1 - \frac{\rho^2}{r^2}\right) P_0 + \kappa \left[ \frac{M^2}{1-M^2} \left(\frac{b^2}{r^2} - 1\right) \ln \frac{M}{r} - \ln \frac{b}{r} \right] \\
\sigma_{e \theta} &= \frac{M^2}{1-M^2} \left(1 + \frac{b^2}{r^2}\right) P_i - \frac{1}{1-M^2} \left(1 + \frac{\rho^2}{r^2}\right) P_0 - \kappa \left[ \frac{M^2}{1-M^2} \left(\frac{b^2}{r^2} + 1\right) \ln \frac{M}{r} + \ln \frac{b}{r} - 1 \right]
\end{align*}
$$

(7)

When $r=\rho$ and $M=\rho/b$, $\rho$ can be calculated by the continuity of stress. Residual strain and stress can be expressed as follows,

$$
\begin{align*}
\sigma_r^e &= \sigma_{r e} - \sigma_r \\
\sigma_\theta^e &= \sigma_{e \theta} - \sigma_\theta
\end{align*}
$$

(8)

Where, $\sigma_r$ and $\sigma_\theta$ are thermal stress (MPa). Temperature stress is the stress caused by the temperature rise and fall of the object, which cannot expand freely or the temperature of each part of the object is different. Also known as “thermal stress”. For example, the stress caused by local heating when the workpiece is welded; Gaps are reserved at the joint of railway rails to avoid or reduce the possible temperature stress. Temperature stress: due to the change of temperature, the structure or component will stretch or shrink, and when the expansion is limited, the stress will be generated inside the structure or component, which is called temperature stress [7].

When the $P_i$ reaches the maximum $P_{\text{max}}$, the internal boundary ($r=a$) will yield inversely, $P_{\text{max}}$ can got if we substitute (7) into the reverse yield condition (9),

$$
\sigma_\theta = \sigma_r t g^2 \left(45^\circ + \frac{\phi}{2}\right) - 2ct g \left(45^\circ + \frac{\phi}{2}\right)
$$

(9)

We can get,
\[ P_{\text{max}} = \left[ \frac{2P_0}{1 - m^2} - \frac{B(1 + K)}{K} - \left( \frac{2}{1 - m^2} + \frac{1}{lnm} \right) \frac{aE\Delta T}{2(1 - \mu)lnm} \right] \left( \frac{1 + 1 + m^2}{1 - m^2} \right)^{-1} \]

Let
\[ \exists = \left( \frac{2}{1 - m^2} + \frac{1}{lnm} \right) \frac{aE\Delta T}{2(1 - \mu)} \]

The formula can be wrote as:
\[ P_{\text{max}} = \left[ \frac{2P_0}{1 - m^2} - \frac{B(T)(1 + K(T))}{K(T)} - \exists \left( \frac{1}{K(T)} + \frac{1 + m^2}{1 - m^2} \right)^{-1} \right] \]

\( E \) and \( \mu \) are the modulus of elasticity (GPa) and Poisson’s ratio. The physical quantity \( \alpha \) involved in formula (9) is coefficient of expansion, \((1/\text{℃})\). The variation of linear expansion coefficient with temperature is similar to that of heat capacity. The absolute value of linear expansion coefficient is closely related to crystal structure and bond strength. Materials with high bond strength have low coefficient of linear expansion. The refractories composed of anisotropic polycrystals and multiphase polycrystals with different values of each phase will produce internal stress in the material during firing and cooling. When the grain boundary is in a high stress state, the strength of the material decreases and even microcracks occur. Porosity also affects the thermal expansion characteristics of refractories. When the porosity weakens the bonding between particles in the material, the value of \( \alpha \) decreases. The closed small pores in the continuous solid phase hardly affect the \( \alpha \) value. The linear expansion coefficient of multiphase, polycrystalline and composite materials can be calculated according to the phase composition. All calculation formulas are based on the premise that there are no microcracks between phases under the action of internal stress, so it is actually an approximate estimation. For refractories with multiple microcracks, the deviation between the measured value and the calculated value of \( \alpha \) can be used as a scale to measure the number of defects in microstructure.

According to formula (11), we will know cohesion and internal friction angle are affected by temperature, their dependence on temperature can be obtained experimentally.

5. Engineering verification
A well called Q in China, is at an altitude of 734 m. By means of inspecting, the cementing of each section did well. The depth of the fracture section ranges 2000 to 3000 m, and the condition out pressure is 40MPa-60MPa. The rock mechanical parameters of cement sheath can be obtained by high temperature and high pressure experiment. The cohesion and internal friction angle are 3.32MPa and 27° respectively. According to the relevant geological conditions, we calculated the theoretical value of the maximum load. From the production diary, we obtained the actual engineering pressure value and compared it with the theoretical value. In some parts, the construction pressure is too high. Gas leakage happened in well section.

Through engineering verification, we believe that the research method can be used in fracturing practice and prevention of wellbore damage. It can also provide an important reference for engineers.

6. Conclusions
Results from the petroleum system, we use a method to the release the issue. Also, a new that has never been used before in petroleum engineering, and is performed on sheath. Through the above analysis, we can draw some conclusions:

- The temperature will cause thermal stress and change of mechanical properties.
- The \( \exists \) shows the destructive action caused by temperature and its size is positively correlated with temperature difference.
- The mechanical parameters of the ring structure can be measured by experiments in order to further measure the adverse effect of temperature on the properties of the cement.
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