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Stress Analysis of Cement Sheath in Thermal Production Well: Effects of High Temperature Changes

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Abstract: In thermal recovery of heavy oil wells, stresses of cement sheath in the oil reservoir section are greater than that of conventional wells, which are due to the action of high temperature and pressure during steam injection. An analytical mechanical model is established, considering pressure and temperature loads coupling effects. The axial stress increase is more significant with the increase of temperature, compared with the radial stress and tangential stress increases, and the effect of temperature increase on the maximum shear stress of cement sheath becomes significant when temperature rise higher than 160℃. When temperature rise above 120℃, effects of temperature increase on maximum shear stress of cement sheath with different elastic modulus are differences, and reducing the elastic modulus of cement sheath is helpful to reduce the maximum shear stress in higher temperature rise. At the same time, when the temperature rise relatively small (below 160-180℃), the effect of steam injection pressure on maximum shear stress is obvious. The axial stress and the maximum shear stress of the cement sheath are increased after casing pre-tension stressed cementing, because the spring back effect of casing will lead to the production of additional axial stress of cement sheath.

Keywords: *Cement sheath, temperature changes, analytical mechanical model, stresses, elastic modulus*

1. Introduction

During the steam injection of heavy oil recovery process, injected steam temperature is usually up to 200-350℃, and the maximum steam pressure is about 17MPa. Steam injection time usually lasts 2 to 10 days according to the physical characteristics of the reservoir. The injected high temperature steam flows through the heat insulation pipe into the wellbore section below the packer, casing and cement sheath in this section are exposed to the high temperature steam environment directly. It is generally believed that casing damage is caused by thermal stresses in the casing failure mechanism of thermal recovery well(Wu et al, 2008; Jaroslaw and Dan, 2009). In fact, not only the casing is affected by the thermal stress, the cement sheath thermal stress also can be produced by the temperature rise. The cement sheath, as a protective sleeve of casing will be threatened by the coupling effect of high temperature rise and pressure.

Goodwin and Crook(1990) carried out a laboratory investigation tosimulate conditions of high temperature changes or excessive internal casing pressure. The experiment demonstrated that sheath stress cracking was caused by diametrical and circumferential casing expansion from excessive temperature increases or excessive internal casing pressures. Jackson and Murphey (1993) performed similar experimental tests, but focused on internal casing pressure changes. Shen and Beck (2012) presented a three-dimensional finite element model to simulate casing and cement sheath mechanical response in interbedded, nonhomogeneous formations. The radial stress of cement sheath was found to be highly variable and affected by the contrast in Young's moduli in the different formation layers. Binh and Azra (2013) established the model and computational results show that cement sheath failure depends strongly on the in-situ stress field of the surrounding formation. The failure of the cement sheath is more severe in a highly anisotropic stress field than in an isotropic field. Albawi et al. (2014) designedanexperimental testing procedure for studying the influence of thermal cycling on annular cement integrityand tested for Arctic conditions. Thermal cycling conditions relevant for Arctic wells causedebondingof the annular cement both at the casing-cement and cement-formation interfaces.Andrade et al. (2015) conceived a laboratory set-up to allow visualizing the development of possible leak paths throughout the cement sheath, such as de-bonded areas and cracks in the bulk of cement, when exposed to pressure and temperature-related varying loads. HonglinXuet al. (2015) established the analysis model of HTHP gas wells to analyze the radial stress and tangential stress of cement sheath, and a safety factor diagram of cement sheath at the weakest casing interface has been drawn by considering wellhead casing pressure ranged from 10 to 70 MPa and wellbore temperature change ranged from -60 to 60℃.

Most of these studies focused on cement sheath radial and tangential stress, and the interface clearance between casing and cement sheath. The axial stress of the cement sheath is not paid enough attention, and the considered temperature changes have not reached the requirements of high temperature steam injection.

In the paper, a mechanical model is established to analyze cement sheath stresses, considering actual conditions (high temperature changes and casing internal pressure) of steam injection in heavy oil recovery process. The effect of temperature increase on maximum shear stress of cement sheath was studied, according to Trescacriterion, and considering the influence of elastic modulus on cement sheath stresses. Negative effects of casing pre-tension stressed cementing on the cement sheath stresses were studied, and the suggestion to prevent the damage of the cement sheath was put forward.

2. Analytical model

2.1 Basic assumptions

The structure of thermal production well is different from that of ordinary oil well. There is a heat insulating pipe from the production casing to the oil layer, and the packer is used to seal the oil layer, and the annular space of the heat insulating oil pipe and the production casing is filled with nitrogen gas. The injection of high temperature steam into the wellbore section below the packer, this section of cement sheath is the research object of the paper, as shown in Figure 1, that affected by the injection of steam temperature (the maximum temperature could reach 350℃), also affected by the steam injection pressure (generally less than 17MPa).

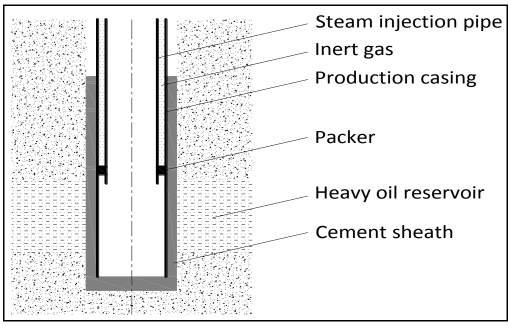

Figure1: *Well structure of oil reservoir in thermal production well*

The model of casing-cement sheath-formation in oil layer is shown in Figure 2. The basic assumptions of model are as follows:

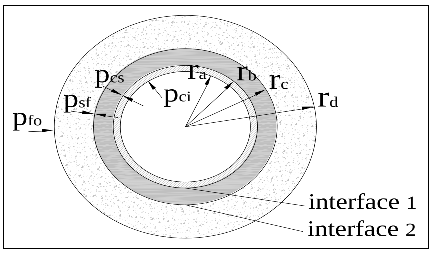

Figure2: *Combined cylinder model of casing-cement sheath-formation*

1. Interfaces of cement sheath and casing (interface 1), cement sheath and stratum (interface 2) are completely cemented, and the combined model is considered as a model of axisymmetric thick walled cylinder.
2. In the axial direction, upper and lower ends of cement sheath in oil layer section are considered as constraint end.
3. Casing, cement sheath and stratum are considered as isotropic materials, and assuming that mechanical properties do not change with the increase of temperature.
4. The in-situ stress near the wellbore is considered to be uniform.

2.2 Model development

Taking into account the influence of temperature, the axial stress, radial stress and tangential stress of the cement sheath are

$$\sigma_{sz} = \mu(\sigma_{sr} + \sigma_{s\theta}) - \alpha_s E_s \Delta T \tag{1}$$

$$\sigma_{sr} = \frac{E_s[(1-\mu_s)\varepsilon_{sr} + \mu_s\varepsilon_{s\theta} - (1+\mu_s)\alpha_s\Delta T]}{(1-\mu_s)(1-2\mu_s)} \tag{2}$$

$$\sigma_{s\theta} = \frac{E_s[(1-\mu_s)\varepsilon_{s\theta} + \mu_s\varepsilon_{sr} - (1+\mu_s)\alpha_s\Delta T]}{(1-\mu_s)(1-2\mu_s)} \tag{3}$$

Equilibrium equation and geometric equations are shown inEqs. (4)-(6).

$$\frac{d\sigma_{sr}}{dr} + \frac{\sigma_{sr} - \sigma_{s\theta}}{r} = 0 \tag{4}$$

$$\varepsilon_{sr} = \frac{du_{sr}}{dr} \tag{5}$$

$$\varepsilon_{s\theta} = \frac{u_{sr}}{r} \tag{6}$$

Radial displacement, radial stress, tangential stress of cement sheathcan be obtained from Eqs. (2)-(6).

$$u_{sr} = \left(\frac{1+\mu_s}{1-\mu_s}\right)\frac{\alpha_s}{r}\int_{r_b}^{r}\Delta T r dr + C_1 r + \frac{C_2}{r} \tag{7}$$

$$\sigma_{sr} = \frac{E_s}{1+\mu_s}\left(\frac{C_1}{1-2\mu_s} - \frac{C_2}{r^2}\right) - \left(\frac{\alpha_s E_s}{1-\mu_s}\right)\frac{1}{r^2}\int_{r_b}^{r}\Delta T r dr \tag{8}$$

$$\sigma_{s\theta} = \frac{E_s}{1+\mu_s}\left(\frac{C_1}{1-2\mu_s} + \frac{C_2}{r^2}\right) + \left(\frac{\alpha_s E_s}{1-\mu_s}\right)\frac{1}{r^2}\int_{r_b}^{r}\Delta T r dr - \frac{\alpha_s E_s \Delta T}{1-\mu_s} \tag{9}$$

Boundary conditions of inner wall and outer wall of cement sheath are

$$\sigma_{sr}\big|_{r=r_b} = -p_{cs} \quad \sigma_{sr}\big|_{r=r_c} = -p_{sf} \tag{10}$$

Substituting Eq. (10) into Eq. (8) yields

$$C_1 = \frac{(1+\mu_s)(1-2\mu_s)}{(1-\mu_s)(r_c^2 - r_b^2)}\alpha_s\int_{r_b}^{r_c}\Delta T r dr - \frac{(1+\mu_s)(1-2\mu_s)r_c^2}{E_s(r_c^2 - r_b^2)}(p_{sf} - p_{cs}) - \frac{(1+\mu_s)(1-2\mu_s)}{E_s}p_{cs} \tag{11}$$

$$C_2 = \frac{(1+\mu_s)r_b^2}{(1-\mu_s)(r_c^2 - r_b^2)}\alpha_s\int_{r_b}^{r_c}\Delta T r dr - \frac{(1+\mu_s)r_b^2 r_c^2}{E_s(r_c^2 - r_b^2)}(p_{sf} - p_{cs}) \tag{12}$$

Cement sheath below the packer are considered to be steady warm-up, namely, $\partial\Delta T/\partial r = 0$. Then substituting Eq. (11)-(12) into Eq. (7) yields

$$u_{rsi} = r_b(1+\mu_s)\alpha_s\Delta T - \frac{r_b(1+\mu_s)(1-2\mu_s)}{E_s}p_{cs} - \frac{2(1+\mu_s)(1-\mu_s)r_b r_c^{\ 2}}{E_s(r_c^{\ 2}-r_b^{\ 2})}(p_{sf}-p_{cs}) \tag{13}$$

$$u_{rso} = r_c(1+\mu_s)\alpha_s\Delta T - \frac{r_c(1+\mu_s)(1-2\mu_s)}{E_s}p_{cs} - \frac{(1+\mu_s)r_c[(1-2\mu_s)r_c^{\ 2}+r_b^{\ 2}]}{E_s(r_c^{\ 2}-r_b^{\ 2})}(p_{sf}-p_{cs}) \tag{14}$$

Casing outer wall displacement and formation inner wall displacement can be obtained in the same way.

$$u_{rco} = r_b(1+\mu_c)\alpha_c\Delta T - \frac{r_b(1+\mu_c)(1-2\mu_c)}{E_c}p_{ci} - \frac{(1+\mu_c)r_b[(1-2\mu_c)r_b^{\ 2}+r_a^{\ 2}]}{E_c(r_b^{\ 2}-r_a^{\ 2})}(p_{cs}-p_{ci}) \tag{15}$$

$$u_{rfi} = r_c(1+\mu_f)\alpha_f\Delta T - \frac{r_c(1+\mu_f)(1-2\mu_f)}{E_f}p_{sf} - \frac{2(1+\mu_f)(1-\mu_f)r_c r_d^{\ 2}}{E_f(r_d^{\ 2}-r_c^{\ 2})}(p_{fo}-p_{sf}) \tag{16}$$

The outer radius of formation is far greater than the radius of the borehole, so Eq. (16) can be written in another form of Eq. (17).

$$u_{rfi} = r_c(1+\mu_f)\alpha_f\Delta T - \frac{r_c(1+\mu_f)(1-2\mu_f)}{E_f}p_{sf} - \frac{2(1+\mu_f)(1-\mu_f)r_c}{E_f}(p_{fo}-p_{sf}) \tag{17}$$

Eq.(18) are established in order to obtain interfaces pressure ($p_{cs}$and p_{sf}), according to interface1 and interface2 displacements continuity.

$$\begin{cases} u_{rco} = u_{rsi} \\ u_{rso} = u_{rfi} \end{cases} \tag{18}$$

Substituting Eq. (11)-(12) into Eq.(8) and Eq. (9)yields

$$\sigma_{sr} = -\frac{(r^2-r_b^{\ 2})r_c^{\ 2}}{(r_c^{\ 2}-r_b^{\ 2})r^2}(p_{sf}-p_{cs}) - p_{cs} \tag{19}$$

$$\sigma_{s\theta} = -\frac{(r^2+r_b^{\ 2})r_c^{\ 2}}{(r_c^{\ 2}-r_b^{\ 2})r^2}(p_{sf}-p_{cs}) - p_{cs} \tag{20}$$

Then axial stress of cement sheath can be obtained from Eqs. (1), (19) and (20).

$$\sigma_{sz} = \frac{2\mu_s(r_b^{\ 2}p_{cs}-r_c^{\ 2}p_{sf})}{r_c^{\ 2}-r_b^{\ 2}} - E_s\alpha_s\Delta \mathrm{T} \tag{21}$$

The maximum shear stress of cement sheath under complex stresses state is shown in Eqs. (22), according to Trescacriterion.

$$\tau_{smax} = \frac{1}{2}max(|\sigma_{sz}-\sigma_{sr}|, |\sigma_{sz}-\sigma_{s\theta}|, |\sigma_{sr}-\sigma_{s\theta}|) \tag{22}$$

3. Case Calculation

3.1 Basic Calculation Parameters

The geometric model is from Bohai oilfield of China. The borehole diameter is 311.2mm, and cemented with Φ244.5mm×11.99mm casing (TP110H). The detailed calculation parameters are listed in Table 1.

Table1: *Basic calculation parameters*

Symbol	Value	Unite	Symbol	Value	Unite
r_a	110.3	mm	α_s	1.1×10^{-5}	1/℃
r_b	122.3	mm	α_f	1.05×10^{-5}	1/℃
r_c	155.6	mm	μ_c	0.2	Dimensionless
E_c	190	GPa	μ_s	0.12	Dimensionless
E_s	10	GPa	μ_f	0.18	Dimensionless
E_f	14	GPa	p_{fo}	14	MPa
α_c	1.2×10^{-5}	1/℃	p_{ci}	10	MPa

3.2 Results and Discussion

3.2.1 Effects of temperature increase on stresses of cement sheath

Fig.3 presents the influence of temperature increase on cement sheath axial stress, radial stress and tangential stress. From Fig.3, it can be learned that the axial stress, radial stress and tangential stress increase with the increase of temperature, and the axial stress increase is more significant, the radial stress and tangential stress are less affected by temperature increase comparing with axial stress. The effect of temperature increase on the maximum shear stress of cement sheath becomes significant when the temperature increase higher than160℃. The tangential stress of cement sheath is less than that of radial stress, whether it is on the interface 1 or the interface 2.

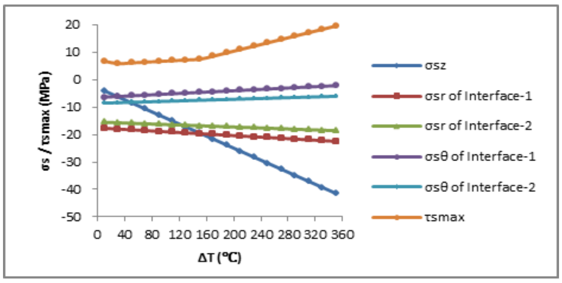

Figure3: *Effects of temperature increase on stresses of cement sheath (conditions of casing internal pressure is 10MPa, and elastic modulus of cement sheath is 10GPa).*

3.2.2 Effects of elastic modulus on stresses of cement sheath

Fig.4 presents the effect of temperature increase on maximum shear stress of cement sheath with different elastic modulus. From Fig.4, it can be learned when the temperature rises above 120℃, effects of temperature increase on maximum shear stress of cement sheath with different elastic modulus are differences. The greater the elastic modulus, the more significant the maximum shear stress is affected by the temperature rise. Reducing the elastic modulus of cement sheath is helpful to reduce the maximum shear stress in higher temperature rise.

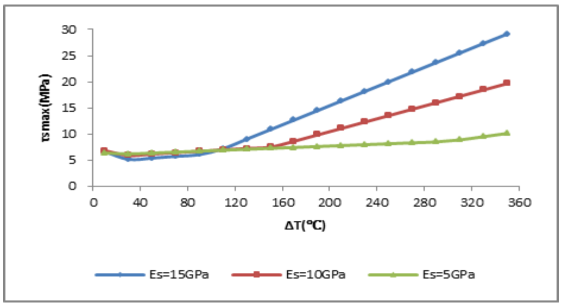

Figure4: *Effects of temperature increase on maximum shear stress of cement sheath with different elastic modulus (the condition of casing internal pressure is 10MPa).*

3.2.3 Effects of steam injection pressures on maximum shear stress of cement sheath

When the steam injection of heavy oil thermal production well, the casing internal pressure will change with the increase of steam injection flow rate. Fig.5 presents the maximum shear stress of cement sheath changes with the temperature rising under different steam injection pressure (i.e. casing internal pressure). It can be seen from Fig.5 that the maximum shear stress increases with the rise of steam injection pressure at condition of the same increase of temperature. At the same time, it can be learned that when the temperature rise relatively small (below 160-180℃), the effect of steam injection pressure on maximum shear stress is obvious, compared to the condition that temperature rise greater than 180℃.

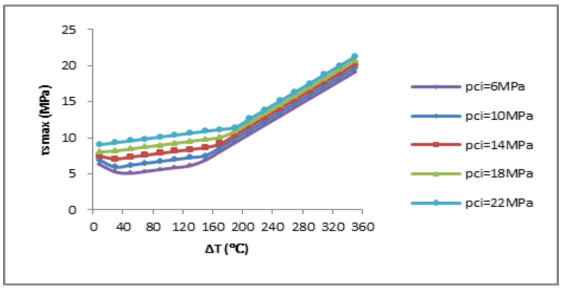

Figure5: *Effects of temperature increase on maximum shear stress of cement sheath with different steam injection pressures (the condition of elastic modulus of cement sheath is 10GPa).*

3.2.4 Effects of casing pre-tension stressed cementing on stresses of cement sheath

In order to avoid the thermal stress of casing exceeding the yield strength, casing pre-tension stressed cementing is implemented (Liu et al, 2008). After completion of well cementing, the spring back effect of casing will lead to the production of additional axial stress of cement sheath. The additional axial stress of cement sheath is

$$\sigma_{sz}{}' = -\frac{E_s F_z}{E_c \pi (r_b{}^2 - r_a{}^2)} \qquad (23)$$

Fig.6 presents effects of casing pre-tension stresses on axial stress and maximum shear stress of cement sheath. The results are calculated based on the parameters of Table 1. Casing pre-tension stresses are calculated based on annular cement displacement height according to the specification for cementing (Writing group of drilling manual, 2012). It can be seen from Fig.6 that axial stress and maximum shear stress of the cement sheath are increased after casing pre-tension stressed cementing. When temperature rises above 160℃, the maximum shear stress of cement sheath is increased 5MPa, compared with casing pre-tension stressed of 157MPa and that of zero.

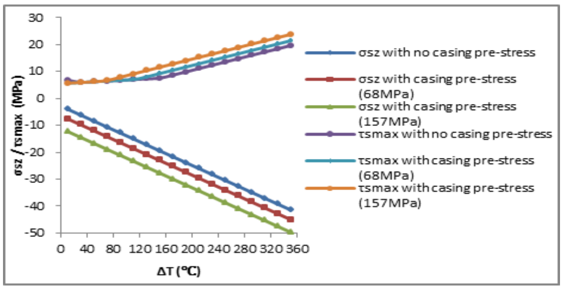

Figure6: *Effects of casing pre-tension stresses on axial stress and maximum shear stress of cement sheath (conditions of casing internal pressure is 10MPa, and elastic modulus of cement sheath is 10GPa).*

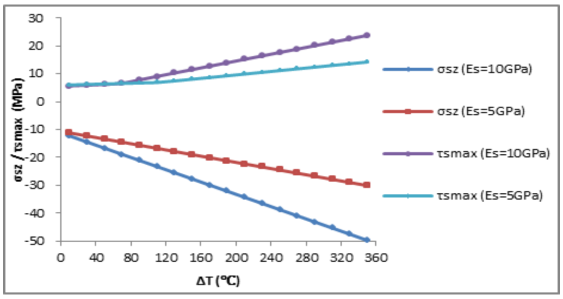

Figure7: *Effects of temperature increase on axial stress and maximum shear stress of cement sheath with different elastic modulus (conditions of casing internal pressure is 10MPa, and casing pre-tension stress is 157MPa).*

Fig.7 presents effects of cement sheath elastic modulus changes on its axial stress and maximum shear stress in condition of casing pre-tension stressed cementing (157MPa). It can be seen from Fig.7that reducing elastic modulus of cement sheath will reduce the axial stress and the maximum shear stress of cement sheath, and effects of elastic modulus on stresses become more significant with the increase of temperature. This regularity is consistent with the conclusion of that in the condition of none casing pre-stressed cementing.

3.3 Suggestions of preventing damage to the cement sheath

In addition to improving the strength of the cement sheath, reducing elastic modulus can also effectively reduce the maximum shear stress of cement sheath significantly under the high temperature steam environment, which can be seen from Fig.4. From the perspective of protecting casing, casing pre-tension stressed cementing technology can prevent casing axial thermal stress is too large in condition of high temperature steam injection. The implementation of casing pre-tension stressed cementing will increase the axial stress and the maximum shear stress of cement sheath, which might aggravate the destruction of cement sheath (role for casing protection). The two aspects effects on casing and cement sheath should be taken into account in the implementation of casing pre-tension stressed cementing.

4. Conclusions

(1) The paper proposed an analytical mechanical model of cement sheath for thermal production wells, considering pressure and temperature loads coupling effects.
(2) The axial stress of cement sheath increase affected by temperature rise is more significant than that of the radial stress and tangential stress.
(3) The greater the elastic modulus, the greater the maximum shear stress is affected by temperature. Cement sheath using smaller elastic modulus can help to reduce the maximum shear stress in higher temperature rise.
(4) The effect of steam injection pressure on maximum shear stress becomes not obvious in condition that temperature rising than 180℃.
(5) The implementation of casing pre-tension stressed cementing technology will increase the axial stress and the maximum shear stress of cement sheath, which have adverse effect on the integrity of cement sheath.

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