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Finite element analysis of influence factors casing based on computer simulation

Mingtao Fan[1], Gonghui Liu[1,2], Jun Lin[1]

Abstract. Technology of staged fracturing on large displacement is adopted to explore shale gas in Sichuan region of China currently, and phenomenon of casing deformation occurs in construction process for a part of shale gas well, seriously affecting normal production of shale gas well. Casing is in complex stress environment due to temperature change in shaft in fracturing process as well as relatively bad well cementation quality, so finite element model of casing-cement sheath-formation stress in temperature-pressure coupling is established in this thesis using software of finite elements, and distribution features of casing stress and combination temperature field in fracturing process is simulated, and influence rule of casing eccentricity, lack of cement sheath on casing stress in different liquid temperature is analyzed. Research result indicates: 1) in fracturing construction of large displacement, casing stress reduces with increase of eccentric distance, and temperature reduction has great influence on casing stress. 2) in different liquid temperatures, variation rule of casing stress with circumference lack of cement sheath is almost the same, and casing stress reduces and then increases with the influence of temperature reduction; 3) radial lack position of cement sheath and variation of depth have relatively little influence on casing stress, and temperature variation is main controlling factor; 4) in the circumstance of casing eccentricity, casing stress will be extremely increased by common effect of lack of cement sheath and temperature reduction. Helpful theoretical guide on exploration of shale gas can be offered by research result of above method.

Key words. Shale gas, Fracturing, Temperature-pressure coupling, Finite element analysis, Lack of cement sheath, Eccentricity

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1. Introduction

Reservoir of shale gas has features of low porosity and extreme low matrix permeability, and production can only be increased via fracturing transformation [1]. Cur-

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rently, staged fracturing technology of horizontal well + hydraulic sand is adopted for exploration of shale gas in Sichuan of China. In the process of staged fracturing and transformation, shaft integrity problem occurs in many wells, namely in follow-up process of fracturing and transformation, damage and deformation of casing occur, thus leading to situations that tripping-in cannot conducted on fracturing tools and drill-grinding cannot be conducted on bridge plug after transformation, and production log cannot be conducted in later period, etc, so it seriously affects smooth proceeding [1–3] of exploration of shale gas.

Directing at the mechanism that load of casing is more than its yield stress leading to casing collapse, influence research of uneven stress load on casing strength due to uneven stress load and well cementing and research on influence rule of uneven load on shear stress of cement sheath and tensile stress on different conditions of eccentricity ratio for casing are developed by a part of scholars.

But it is found from features of fracturing operation of shale gas that perforation and reservoir reform need to be conducted on more than ten well sections during well completion period for highly-deviated well and horizontal well, and perforated interval of a single section is relatively long and reformation scale is great. With rapid pouring of fracturing liquid of large displacement, shaft temperature will quickly reduce. Secondly, phenomenon of partial lack of cement sheath will occur due to cement channeling and perforation well completion operation, etc in the process of pouring cement on cement job of horizontal well. Complex stress environment of casing is caused in process of fracturing by these features. Currently, there are few researches on influence of cementing quality on casing stress in the effect of temperature of shale gas well. So finite element model of casing-cement sheath-formation in temperature-stress coupling is established based on anisotropy of shale formation by the writer, and influence of temperature reduction for shaft and cementing quality on casing stress in process of liquid pouring is comprehensively considered in aim of offering theoretical basis for smooth proceeding of follow-up construction operation.

2. Laboratory experiment of property parameter on rock mechanics

Core from site can only conform to experimental requirement after reprocessing. Generally core in shape of cylinder (φ25mm) will be drilled with diamond core bit before test experiment of rock mechanics, then two ends of core shall be flattened with lathe in guarantee that ratio of height and diameter for rock sample is 1.8:2.0. Due to severe water sensitivity of shale, kerosene is used as circulating cooling liquid in process of coring to prevent nature change of core. To research anisotropy of core, coring of rock sample is divided into four different directions, namely of 0°, 15°, 30°, 45°60°, 75°, 90° to nominal direction of bedding plane. Schematic map of coring on rock sample is shown in Fig. 1. Value of elasticity modulus and Poisson ratio with variation of bedding plane is shown in Fig. 2 and Fig. 3.

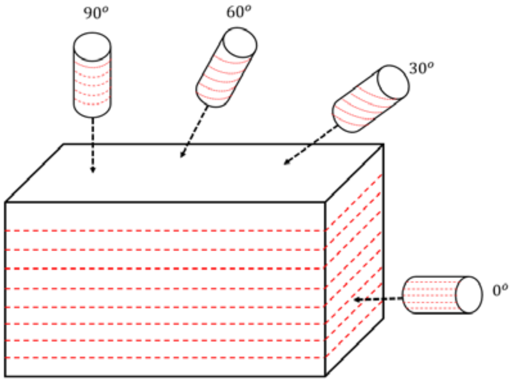

Fig. 1. Map of coring sampling

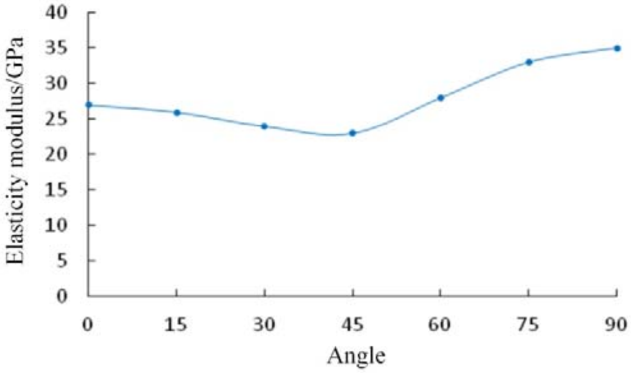

Fig. 2. Value of elasticity modulus with angle variation of bedding plane

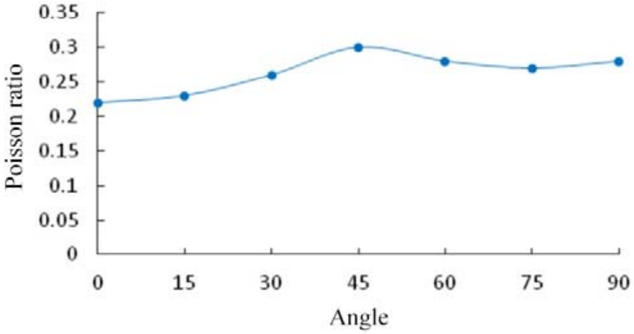

Fig. 3. Value of Poisson ratio with angle variation of bedding plane

3. Theoretical model of anisotropic elastic deformation for shale on bedding formation

There is natural fracture of shale reservoir and directivity of bedding configuration, especially there is obvious anisotropy of elastic parameters for planes parallel to and perpendicular to bedding plane. Transverse isotropic features of bedding formation shale are considered in this thesis. Bedding formation is the simplest form of anisotropic formation, and shale is usually considered as a model of bedding formation in engineering. Stress-strain features of shale on bedding formation are isotropous, and they can be described with five independent elastic constants. Liner elastic relationship of stress and strain in elastomer is reflected in Hooke's law, and its constitutive equations of stress-strain can be presented as for anisotropic material:

$$\{\varepsilon'\} = D^{'-1}\{\sigma'\} ,$$

$$D^{'-1} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_y} & -\frac{\nu_{xz}}{E_z} & & & \\ -\frac{\nu_{xy}}{E_y} & \frac{1}{E_y} & -\frac{\nu_{yz}}{E_z} & & & \\ -\frac{\nu_{xz}}{E_z} & -\frac{\nu_{yz}}{E_z} & \frac{1}{E_z} & & & \\ & & & \frac{1}{G_{yz}} & & \\ & & & & \frac{1}{G_{xz}} & \\ & & & & & \frac{1}{G_{xy}} \end{bmatrix} .$$

In the formula: $E_x = E_z$ is elastic modulus parallel to isotropic planes; E_y is elastic modulus perpendicular to isotropic planes; V_{xz} is Poisson ratio parallel to isotropic planes; $V_{yz} = V_{xy}$ is Poisson ratio perpendicular to isotropic planes.

Shear modulus in XOZ of isotropic planes is:

$$G_{xz} = G_h = \frac{E_h}{2(1+v_h)} .$$

In the formula: G_h is shear modulus parallel to isotropic planes, and GPa;E is elastic modulus parallel to isotropic planes, and GPa: v_h presents Poisson ratio parallel to isotropic planes.

Mathematics-based method of $G_v = G_{yz} = G_{xy}$ for the fifth elastic constant of planes YOZ and XOY perpendicular to isotropic planes was proposed by Batugin, etc, and it was verified via plenty of experimental data [12]:

$$G_V = G_{yz} = G_{xy} = \frac{E_y E_z}{E_y + E_z + 2\nu_{yz}E_z} .$$

4. Basic theory of fluid-solid coupling problem

It is deemed in consolidation theory of Terzaghi that total stress distribution of soil body does not change in process of consolidation, but process of stress loading is ignored, so there is limitation for this kind of hypothesis on three-dimensional model. Biot offered "real three-dimensional consolidation theory" from the perspective of relatively strict consolidation mechanism, and it could truly reflect relationship of pore pressure change and rock deformation. If macro isotropy, liner elasticity, deformation, seepage isotropy of rock satisfy Darcy law, then Biot Consolidation Equation[13] represented with displacement and pore pressure is:

Among it, $\nabla^2 = \left(\frac{\partial^2}{\partial x} + \frac{\partial^2}{\partial y} + \frac{\partial^2}{\partial z}\right)$.

In the formula: G is shear modulus; v is Poisson ratio of solid particles; u is stress of pore fluid; is unit weight of fluid; k is permeability coefficient of solid particles; w is overall displacement; is Laplace operator. In the formula, the fore three are differential equations of consolidation, and the fourth is continuity equation of fluid. Three unknown quantities u^s, ν^s, w^s included in the equation can be solved on certain initial condition and boundary condition.

5. Establishment of finite element model

5.1. Establishment of local coordinate system and determination of sensitive parameters for finite element

Transverse isotropic features of bedding formation shale shall be considered, and local coordinate system ( ) of material is established after establishment of numerical model. If world coordinates of established formation model is XYZ, and isotropic plane is X-Z, and symmetry axis is Y axis, and drilling of horizontal well is conducted along direction of minimum horizontal primary stress. Local coordinate system of bedding formation for shale is X' Y' Z', and local coordinate system is one-to-one correspondence to three-axis of global coordinate system, namely X-X', Y-Y', Z-Z'. Among it, Z' axis is located in isotropic plane, and Y' is symmetric rotation axis of bedding plane.

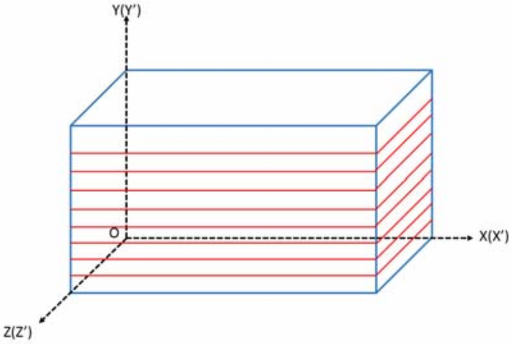

Fig. 4. Global and local coordinate system of bedding shale

5.2. Establishment of model

Direct coupling is conducted on combination temperature field and stress field with software of finite element adopted in this thesis. External loading from distant field stress and inside casing is commonly supported by combination of casing-cement sheath-formation in this model. To reflect formation response more truly and avoid error brought by model dimension, initial ground stress and initial temperature are loaded on combination via predefined field function in software of finite element in the simulation, then complete restraint on outer boundary is conducted. Heat transfer way of combination is transient heat transfer [14,15]. It is assumed in the model that:

1) Rock heat transfer is only considered in direction of axis on vertical well in combination of heat transfer;

2) Thermal physical natures (density, specific heat and pyroconductivity) of combination are not affected by temperature;

3) Casing, cement sheath and formation are all isotropic material;

4) There is close contact and no sliding among combinations;

Specific geometrical parameter, material feature and thermodynamic parameter of combination model are shown in Table 1 and 2.

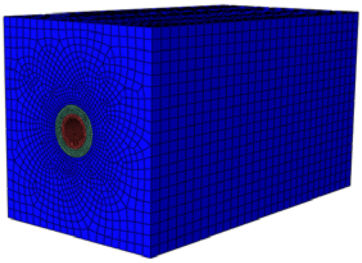

Fig. 5. The combination finite model of casing-cement sheath-formation

Table 1. Geometrical parameter and material characteristics of casing-cement sheath

Medium	/mm External diameter	/mm Internal diameter	/GPa Elastic modulus	Poisson ratio	/o Internal friction angle	/MPa Cohesion
Casing	139.7	120.3	210	0.3	-	-
Cement sheath	215.9	139.7	9	0.15	17.1	21.6

Table 2. Thermodynamic parameters of model material

Medium	/(kg·m-3) Density	/oC-1 Swelling coefficient	/(J·kg-1·oC-1) Specific heat	/(W·m-1·oC-1) Heat conductivity coefficient
Casing	7800	1.22e-5	460	45
Cement sheath	1800	1.05e-5	865	0.9
Formation	2300	1.03e-5	896	2.2

In process of fracturing construction of shale gas well, high pump pressure of large displacement will be adopted to conduct reservoir reform, and continual pouring of fluid will lead to dynamic change of shaft temperature field, and combination load will change [5] as time goes by in process of transient heat transfer, so initial temperature of formation is chosen at 100 degrees, and liquid pouring temperature is set at 0 degree, and liquid pouring time is one hour for model parameters in this thesis. Among it, initial hydrostatic fluid column pressure is 10 MPa, and pressure in shaft at the time of liquid pouring is 90 MPa. For well track of horizontal well for shale gas is generally parallel [10] to direction of horizontal minimum principal stress, boundary loading of model can be set as: horizontal maximum principal stress is represented in horizontal direction, and vertical principal stress is represented in vertical direction, and the numbers are respectively σV=30MPa, σH = σh 20 MPa. Elastic modulus of rock is: Ey=27GPa; EX=EZ=27~35GPa; Poisson ratio of rock is: vy=0.223; vx=vz=0.242; Formation saturability is: 100%; porosity: 3%; fluid density: 0.98g/cm3; permeability rate: 1.0 e-3um2; pore pressure: 5 MPa.

6. Anisotropic influence

It is defined that ratio of elastic modulus for shale bedding plane to nominal elastic modulus of bedding plane is K, and K = Ev /Eh, and ratio of Poisson ratio for bedding plane to nominal Poisson ratio of bedding plane is K', and K' = Vv /Vh. K and K' are both reference values indicating the anisotropic degree of material, and a greater value indicates a higher anisotropic degree.

It can be found in Fig. 6 that heterogeneity of combination force increases on different liquid pouring temperature at the time of considering anisotropy of elastic modulus, but overall increase is not great, and stress influence of temperature on casing is the main controlling factor. It can found in Fig. 7 that influence of anisotropy for Poisson ratio on casing stress is almost zero. To sum up, heterogeneity of combination force will be increased by anisotropy of elastic modulus, but influence of anisotropy of elastic modulus on casing stress is relatively little.

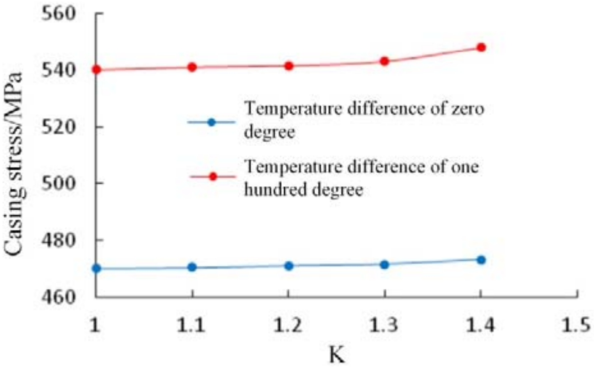

Fig. 6. Influence of anisotropy of elastic modulus on casing stress

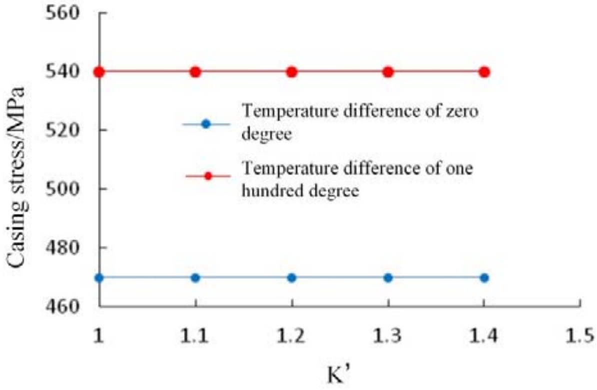

Fig. 7. Influence of anisotropy for Poisson ratio on casing stress

7. Influence of casing eccentricity

Exploitation is usually conducted via horizontal well technology in development process of shale reservoir, but because gravity direction of highly-deviated well section and horizontal well section in process of casing running is radial rather than axial, and it is extremely easy to result in casing eccentricity, thus producing difference [11] of cement sheath thickness for external casing wall after well cementation.

Finite element model of casing eccentricity is established at temperature-pressure coupling directing at this phenomenon. As is shown in Fig. 8, well center is point O, and casing center is point O', and eccentric distance is e, and eccentric angle is Φ [12]. Eccentric angle of casing is set at $0°$, and eccentric distance is set at 30 mm in the model. After simulation, choose some nodes in internal wall of casing clockwise, extract corresponding parameter value, draw corresponding change curve of parameters to node path.

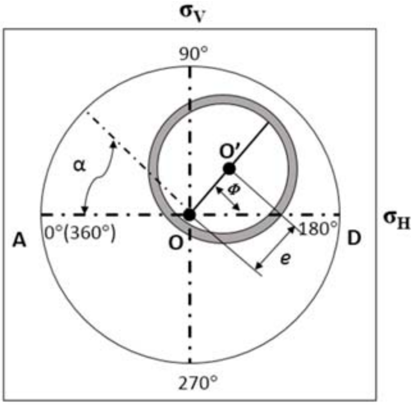

Fig. 8. Combination model of casing-cement sheath-formation

From Fig. 9, formation temperature reduction mainly occurs near shaft after one hour of liquid pouring. At casing eccentricity, shaft temperature field overally presents change of heterogeneity, and thermal disturbance distance in direction of eccentricity is relatively great, meanwhile casing temperature in this direction is relatively high. This is because heat conductivity coefficient of cement sheath is lower than that of formation, and thickness of cement sheath in eccentric direction is relatively small, so thermal resistance in this direction within certain distance near shaft is relatively small, thus leading to relatively great [13] heat quantity transferred in eccentric direction in unit time.

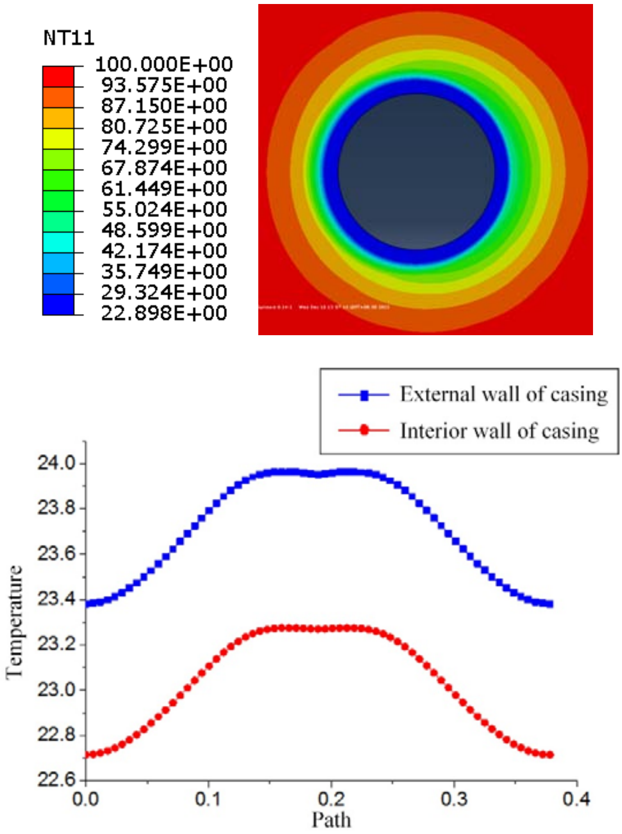

Fig. 9. Temperature field distribution around wells (liquid pouring for an hour)

Influence of casing eccentricity on casing stress is shown in Fig. 10 at different liquid pouring temperature. It can be found that maximum stress of casing reduces a little with pumping in of high-pressure fluid when eccentric distance of casing is 30 mm, and casing stress reduces relatively obviously in section of 90° and 270°. When liquid pouring temperature is zero degree, change rule of casing stress is almost the same. Compared with situation where temperature is not considered, casing stress increases obviously caused by pouring of cooling fluid, and growing rate is about 19%.

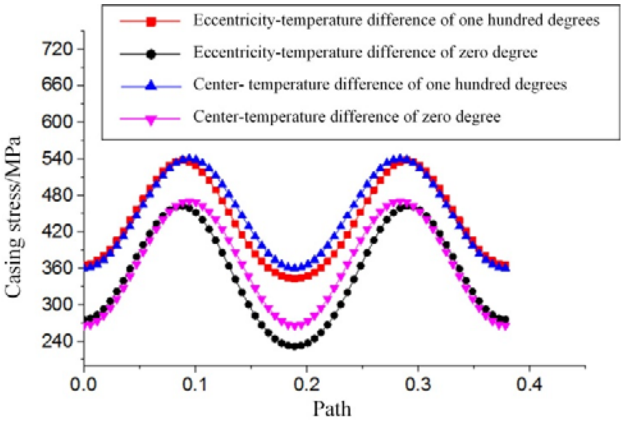

Fig. 10. Casing stress distribution at different liquid pouring temperature

Casing stress change quantity caused by temperature reduction is shown in Fig. 11 at different liquid pouring temperature, and it can be found that as liquid pouring temperature decreases, influence of casing eccentricity on casing stress gradually weakens. At casing eccentricity, temperature loading produced by temperature reduction of liquid pouring is the main reason leading to increasing of casing stress.

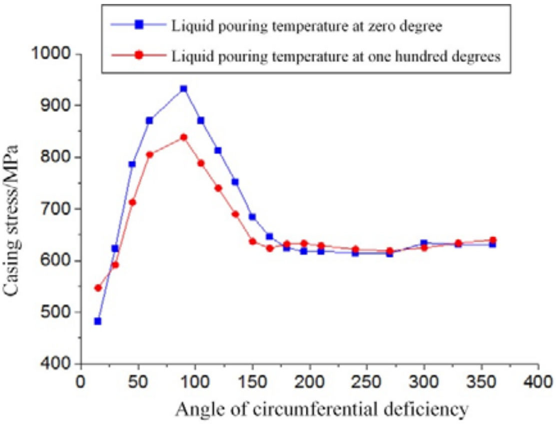

Fig. 11. Influence of eccentricity on casing stress at different liquid pouring temperature

8. Influence of lack of cement sheath

Predecessors found that defect formation of cement sheath is complex [14–18] in real circumstances via on-site and indoor experiments. So the writer respectively researches the change rule of casing stress on effect of circumferential deficiency, different deficiency depth and deficiency position of cement sheath, and on combination effect of casing eccentricity as well as lack of cement sheath.

8.1. Circumferential deficiency

As shown in Fig. 12: deficiency angle of cement sheath is α, and circumferential angle along horizontal direction clockwise is 0-360° in sequence. Casing in the model is in the middle, then eccentric distance is 0 mm, and eccentric angle is 0°, so 0-360° can be chosen as deficiency angle of cement sheath to conduct simulated calculation. Setting of model material parameter and correspondent stress parameters does not change.

Temperature field distribution rule around wells is shown in Fig. 13 at the time of circumferential deficiency of cement sheath. It is found in the research that casing deforms too greatly to contact formation due to insufficient inner pressure of casing, so formation temperature where cement sheath deficiency occurs is mainly affected by contact area of cement sheath at both sides and formation, and it overally presents the shape of a funnel. And with increase of circumferential deficiency, contact area of casing and cement sheath gradually decreases, thus causing gradual reduction of minimum temperature for casing.

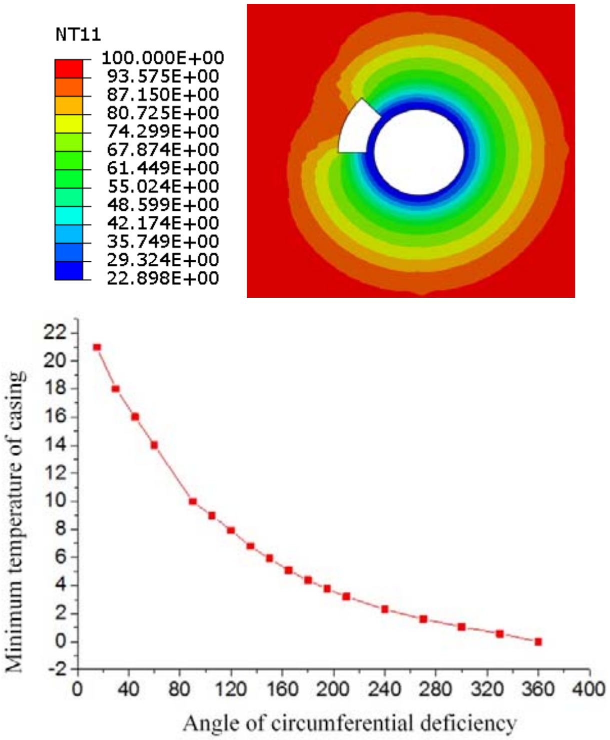

Fig. 12. Temperature field distribution of shaft at circumferential deficiency of cement sheath

Change rule of casing stress at the time of different angles for circumferential

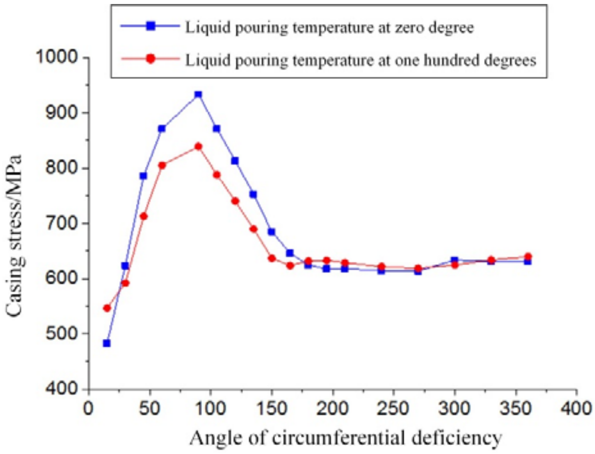

Fig. 13. Maximum stress of casing at different liquid pouring tempertaures

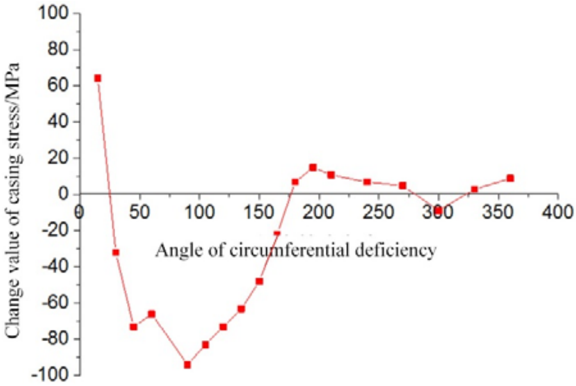

Fig. 14. Influence of liquid pouring temperature on casing stress

deficiency of cement sheath at different liquid pouring temperature is shown in Fig. 14. It can be found in the figure that change rule of casing stress with lack of cement sheath is almost the same at different liquid pouring temperature: namely obvious stress concentration will occur in where cement sheath deficiency occurs, and casing stress rapidly increases, reaching maximum at around 90° when lack of cement sheath occurs. Later casing stress gradually reduces with increase of deficiency angle of cement sheath. When deficiency angle is , casing stress reduces to 620 MPa, but deformation damage such as shear and squeezing, etc of casing probably occur in later processes of fracturing transformation and oil well production because there is no protection of cement sheath for casing this moment. It can be found integrating Fig. 14 and 7 that casing stress firstly reduces and then increases overally with increase of deficiency angle of cement sheath with the influence of temperature reduction. Namely when deficiency angle is relatively small, the lower the liquid pouring temperature, the greater the casing stress, later temperature reduction in shaft with increase of deficiency angle, causing reduction to different degrees of casing stress.

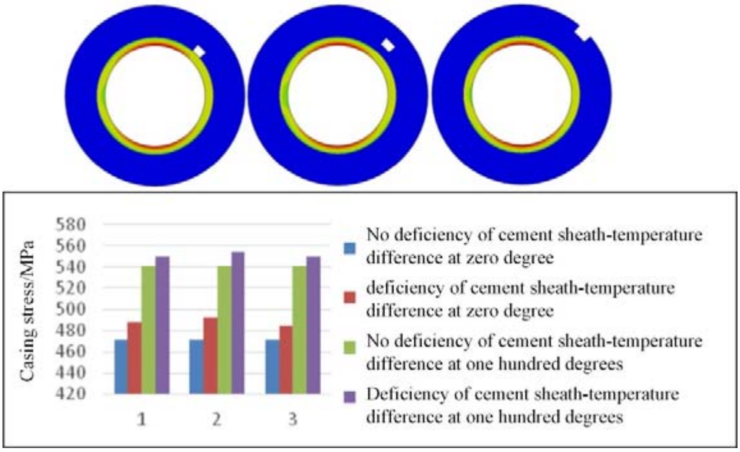

Fig. 15. Maximum casing stress at different liquid pouring temperature

8.2. Radial deficiency position

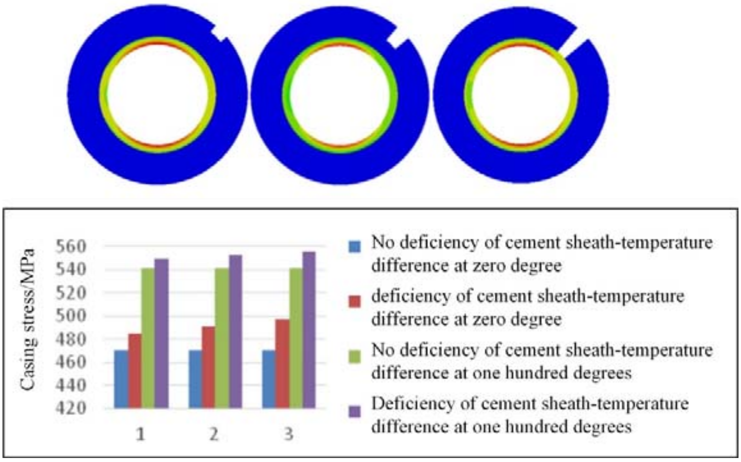

Fig. 16. Maximum casing stress at different liquid pouring temperature

Influence of radial deficiency position for cement sheath on casing stress is shown in Fig. 15 at different liquid pouring temperature. Among it, circumferential opening is set at 10° with orientation at 135° where cement sheath deficiency occurs, and relative depth of deficiency is set at 10 mm. It can be known via calculation that when temperature influence is ignored, casing stress firstly increases and then reduces if deficiency position of cement sheath is transferred from the first interface to the second interface. When influence of fluid pouring temperature is considered, change rule of casing stress is almost the same, and temperature reduction in the shaft causes maximum stress growing rate to reach 14% of casing, meanwhile when deficiency position of cement sheath changes, casing stress reduces to some extent with temperature reduction in the shaft.

8.3. Deficiency depth

Influence rule of deficiency depth of cement sheath on casing stress is shown in Fig. 16 at different liquid pouring temperature. Among it, circumferential opening is set at 10° with orientation at 135° where cement sheath deficiency occurs, and relative depth of deficiency is from internal boundary to external boundary of cement sheath. It can be known form the figure that when deficiency depth is small, casing stress increases by 14 MPa, and casing stress continually increases with increase of deficiency depth of cement sheath, and maximum growing rate is 26 MPa. Change rule of casing stress in effect of different temperature is almost the same, temperature reduction in the shaft causes casing stress to increases by about 13%, and influence difference of deficiency depth of cement sheath on casing stress is reduced.

8.4. Casing eccentricity + deficiency of cement sheath

Eccentric distance in the model is set as 30 mm, and eccentric angle is set as, namely the direction of horizontal maximum main stress, and deficiency form of cement sheath is crescent deficiency, and deficiency position is shown in Fig. 17, and other parameter setting does not change. Influence rule of combination effect of casing eccentricity and deficiency of cement sheath on casing stress can be concluded via simulative calculation at different liquid pouring temperature. As is shown in the figure, when deficiency position of cement sheath is at , casing stress increases with reduction of temperature inside the shaft, and when deficiency position is at , namely direction of casing eccentricity, casing stress reduces with reduction of temperature inside the shaft. Meanwhile it can be found that at different liquid pouring temperature, casing stress obviously increases when deficiency of cement sheath in the direction of casing eccentricity occurs.

9. Conclusion

Combination model where casing eccentricity and deficiency of cement sheath are taken into consideration is established in this thesis, and influence of temperature and well cementing quality on casing force is analyzed in fracturing construction operation where coupling of temperature field and stress field is conducted. It is found in the research that:

1) Influence of overall formation anisotropy on combination stress is not great;

2) During the period of high-pressure liquid pouring, heterogeneous distribution of shaft temperature field is caused by difference of casing eccentricity and heat conductivity coefficient of combination. Temperature change of formation mainly

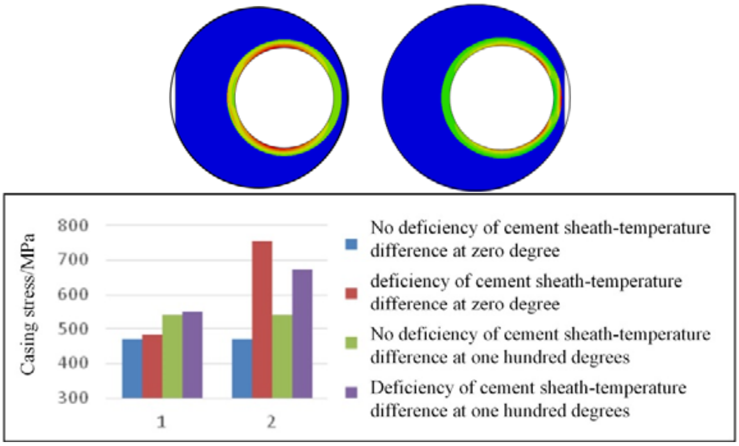

Fig. 17. Maximum casing stress at different liquid pouring temperature

focused on area near the shaft is decided by construction time, relatively low heat conductivity coefficient of cement sheath and formation, and temperature reduction is the main reason leading to increase of casing stress.

3) At the time of circumferential deficiency of cement sheath, change trend at different liquid pouring temperature is almost the same, and casing stress overally reduces and then increases with the influence of temperature.

4) Radial deficiency of cement sheath in different degrees can all lead to increase of casing stress to some degree, but the influence of maximum casing stress on change of deficiency depth and deficiency position is not obvious, and influence of this factor on casing stress will be reduced by temperature reduction in the shaft.

5) When deficiency of cement sheath in the direction of casing eccentricity occurs, temperature reduction and deficiency of cement sheath can both cause obvious influence to casing stress.

It can be found according to above research conclusion that influence of temperature loading due to temperature reduction and well cementing quality on casing intensity cannot be ignored in fracturing construction operation of oil well, and it shall be considered. In later construction operation, operation parameters such as pumping pressure, displacement, etc shall be optimized meanwhile to ensure smooth conduction of oil well transformation in premise of guaranteeing well cementing quality.

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