A new numerical method for evaluating the variation of casing inner diameter after strike-slip fault sliding during multistage fracturing in shale gas wells

Yan Xi | Jun Li | Gonghui Liu | Chunqing Zha | Xiamao Zeng | Wenli Zhong

Abstract
Casing shear deformation has become a prominent problem in the process of completion in shale gas wells. It was believed that the slide of strike-slip fault induced by multistage fracturing was the main reason. This paper presented a new numerical investigation for evaluating the casing inner diameter after strike-slip fault sliding based on the microseismic data. A 3D finite element model, considering the mechanical anisotropy of shale and heat-fluid-solid coupling effect during multistage fracturing, was developed to calculate the variation of casing inner diameter after fault sliding under different engineering and geological conditions. The calculation result was verified by comparison with the measurement result of the multi-finger caliper survey. Sensitivity analysis was carried out and the results showed that decreasing the sliding distance, maintaining high pressure, increasing the casing thickness, and increasing the elasticity modulus and decreasing the Poisson ratio of cement sheath were beneficial to protect the casing integrity. Finally, the engineering verification demonstrated that the numerical method has an accuracy up to 85.9%. Numerical model in this study was expected to provide a better understanding of casing shear deformation and an evaluation method of casing inner diameter after fault sliding during multistage fracturing in shale gas wells.

KEYWORDS
casing shear deformation, microseismic data, multi-finger caliper, multistage fracturing

1 | INTRODUCTION

Casing deformation occurred during multistage fracturing, which increased the cost of well completion obviously and decreased the productivity of shale gas wells significantly, attracted more and more attention in all over the world, especially in the countries which made major breakthroughs in developing shale gas, such as the United States, Canada, and China. Previous studies showed that production casing deformation appeared frequently after several stages of fracturing operation in shale gas wells, which became a challenging issue in the process of completion in shale gas wells. Some scholars pointed out that the production casings were under severe deformation during multistage fracturing in some shale gas fields in the United States. Multi-Finger Caliper (MFC) surveys were carried out in five pads including 28...
wells in Southern Simonette, Canada, the measurement results showed that casing deformation occurred in 16 wells, 23 deformed points were found. As of June 2018, 180 horizontal wells were hydraulically fractured in WY-CN shale gas field, China, casing deformation occurred in 79 wells. And not only that, productivity testing was implemented in different wells but in the same pad, the comparison result indicated that the tested outputs of the wells suffering from casing deformation were on average 29.1% lower than the wells without casing deformation. In this sense, it is important and necessary to do the research on studying the mechanism of casing deformation and putting forward solutions to reduce its negative impacts.

According to the logging data and morphologies of lead impression blocks, there were five different types of casing deformation, including extrusion deformation, shear deformation, bending deformation, buckling, and casing hole. Casing shear deformation comprised the majority of all the types of deformation. Statistics revealed that 61.7% of all the 48 deformed points in WY-CN shale gas field and 52.2% of all the 23 deformed points in Simonette were all due to shear deformation. As a result of this, casing shear deformation was turned to be the focus of research. Though there were a lot of trials about casing shear deformation by now, most of the studies lay the research emphasis on the induction factors. Based on the relevant theories and studies, the pre-existing fractures played a critical role during the progress of fault sliding. After fracturing fluid flowed into the fractures, the pore water pressure increased, the effective normal stress and friction coefficient of the interface decreased, then the fault was more likely to be reactivated and slide along the pre-existing fracture. In the research of Bao et al, it was believed that fault activation could appear during or after hydraulic fracturing, the changes of geostatic stress or pore pressure were the main reason of triggering fault sliding. According to the microseismic imaging of hydraulic fracturing, Meyer et al suggested that shear failure of pre-existing faults in the shale formation was likely the main cause of casing shear deformation. In addition, some scholars noted that even unassuming malleable fractures could create a low strength surface during hydraulic fracturing, it also could accelerate the fault movement. It was well known that the original bridge plug could not pass through the deformed part of the production casing after fault sliding; hence, selecting the new appropriate bridge plug according to the casing inner diameter was the key to continue the multistage fracturing. But few of the current researches analyzed the variation of casing inner diameter after fault sliding.

The occurrence of multi-finger caliper (MFC) provided a practical and effective method for dealing with this kind of problems. Some scholars analyzed the MFC measurement results of conventional and unconventional oil and gas, pointed out that MFC was an effective tool to identify the morphology of the deformed part and measure the variation of casing inner diameter along the axial direction. Marc carried out approximately 30 MFC surveys in Elgin and Franklin, demonstrated that the shear deformation features were localized over a relatively short length (several feet). In the report of Saada et al, MFC proved to be an efficient method of assessing the inner condition of the production casing after deformation. As the casing shear deformation occurred during multistage fracturing, MFC tool was used in some wells. Based on the measurement results, the geomechanical model was established to analyze the relationship between the microseismic magnitude and casing shear deformation, and the analysis result showed that the greater the magnitude, the greater the risk of casing deformation. Guo et al developed a numerical model based on the MFC measurement results, calculated the influences of sliding distance, sliding angle and mechanical parameters of cement sheath on casing stress. Despite the clear benefits of MFC surveys, this kind of technique remains challenging to implement in the extensive regional oil and gas field due to the significant cost of a full system. As a result of this, there are merely few studies that provide the evidence of MFC data and conduct some prospective studies. Synthesizes the above analysis, it is very necessary to develop a new method to calculate the variation of casing inner diameter after production casing shear deformation occurred and analyze differences of the variation under different engineering and geological conditions, so as to provide evidence for mitigation measures.

In this study, the relationship between microseismic moment magnitude and sliding distance was established. A 3D numerical model, considering the mechanical anisotropy of shale and heat-fluid-solid coupling effect during multistage fracturing, was developed to quantify variation of casing inner diameter after fault sliding. The solid-shell technique was used to improve the accuracy of the calculation. The calculated result was verified by comparison with the measurement result of the MFC survey. Sensitivity analysis was carried out, and the variations of casing inner diameter under different material and mechanical parameters were analyzed. Finally, three engineering cases were studied, and the comparison results indicated that the numerical method could be used to assess the casing inner diameter after fault sliding.

2 | ANALYSIS OF FAULT SLIPPING

There are three types of faults, including normal fault, reverse fault, and strike-slip fault. Recent studies showed that fault activity occurred during multistage fracturing appeared to be associated with a strike-slip stress regime (S_{max} > S_{Vertical} > S_{min}) in Sichuan basin, China. Vast engineering practice indicated that 78% of the microseismic
events had a strike-slip failure mechanism in Southern Simonette, Canada. Thus, it could be inferred that the strike-slip fault sliding was the main reason of casing shear deformation.

As a result of this, take strike-slip fault as an example. Previous researches demonstrated that the fault would slide after fracturing fluid flowed into the pre-existing fracture when

\[ \tau > f_n (S_n - P_p) + S \]  

where \( \tau \) represents the shear stress applied to the fault, MPa; \( f_n \) represents the coefficient of friction, dimensionless. And according to Zoback (2010), the value range of \( f_n \) is from 0.6 to 1.2. \( S_n \) represents the effective normal stress, MPa; \( S \) represents the rock cohesive strength, MPa; \( P_p \) is the pore pressure, MPa; \( S_n \) is the normal stress perpendicular to the interface, MPa.

Under this condition, the minimum increment of pore pressure which could cause the fault sliding was as follows:

\[ P' = \frac{S}{f_n} + \sigma_3 + (\sigma_1 - \sigma_3) \left( \frac{\sin^2 \psi - \sin \psi \cos \psi}{f_n} \right) \]  

where \( P' \) represents the minimum increment of pore pressure, MPa; \( \psi \) is the angle between the interface and the maximum horizontal principal stress, \( \sigma_1 \) and \( \sigma_3 \) represent the maximum and minimum principal stress, MPa.

Once the fault slid, there were increasing occurrences of seismicity associated with fault activation during multistage fracturing. According to the measurement results of microseism, fault radius could be expressed using the following equation

\[ r_0 = \sqrt[3]{\frac{7 \times 10^{(1.5M_w + 9.1)}}{16\Delta \sigma}} \]  

where \( r_0 \) represents the radius of the slip fault, m; \( M_w \) represents the microseismic moment magnitude, dimensionless; \( \Delta \sigma \) represents the stress drop, Pa. Both \( M_w \) and \( \Delta \sigma \) can be measured based on the microseismic survey.  

Then the fault sliding distance could be calculated by

\[ D = \frac{16 \Delta \sigma r_0}{G \pi} \]  

where \( D \) represents the sliding distance, m; \( G \) represents shear modulus, Pa, and it can be calculated \( G = E/2(1 + \nu) \); \( E \) represents elasticity modulus, Pa; \( \nu \) represents Poisson’s ratio, dimensionless.

From the above analysis, it can be seen that \( M_w \) and \( \Delta \sigma \) were the two important parameters for evaluating the slip distance. Some scholars pointed out that West Canadian reservoirs and Sichuan Basin in China experienced anomalous activity during multistage fracturing, the microseismic moment magnitude was more than 4.26-29 Engineering monitoring in this study proved this point, the maximal moment magnitude reached 4.3. In the research of Mukuhira et al (2013) and Chen et al (2017), the stress drop of most of the microseismic events occurred during multistage fracturing was between 0.1~1 MPa.  

### 3 | NUMERICAL SIMULATION

Finite element method (FEM) was often used to study the complicated rock mechanics problems in hydraulic fracturing. A three-dimensional (3D) nonlinear FEM was developed to simulate the progress of fault sliding and evaluate the variation of casing inner diameter after fault sliding by using the commercial software Abaqus (6.14-1). The following were the specifics of the numerical model.

![Research object and numerical model of fault sliding](image)
3.1  |  Numerical model

3.1.1  |  Geometry

The model was comprised of casing, cement sheath, and formation. The outer diameter of the model was a 3 m × 3 m × 8 m cuboid, the size of which was ten times greater than that of the borehole, so as to avoid the influence of the boundary on the stress. The formation in the model was composed of two blocks, one was the fixed part and the other was the sliding part, which could slide along x-axis negative direction (Figure 1). The interaction between the formation (wellbore rock) and cement sheath was set as tie, and it between the cement sheath and casing was set as hard contact, the friction formulation was penalty and the coefficient was 0.6. In addition, it was assumed that the casing remained centered and the cement sheath showed complete integrity.

3.1.2  |  Coordinate systems

Shale exhibits the characteristic of strong anisotropy as being layered materials, which should be taken into account in order to reflect the real mechanical environment. For this reason, the anisotropic parameters of the formation were calculated

| TABLE 1  | Mechanical properties of casing, cement sheath, and formation |
|----------|---------------------------------------------------------------|
|          | Young modulus (GPa) | Poisson’s ratio | Friction angle (°) | Cohesive force (MPa) | Coefficient of heat conduction (W/(m²°C⁻¹)) | Specific heat (J/(kg°C⁻¹)) | Density (kg/m³) | Coefficient of thermal expansion (10⁻⁶°C⁻¹) |
| Casing   | 206                | 0.3            | \              | \                  | 45                  | 461                  | 7800          | 13                        |
| Cement sheath | 10          | 0.17           | 27             | 8                  | 0.98               | 837                  | 3100          | 11                        |
| Formation | 40                | 0.23           | 30             | 5                  | 1.59               | 1256                 | 2600          | 10.5                       |

FIGURE 2  | Discrete fracture network with events
according to the Attachment A and then were imported into the local (material) coordinate system (X’Y’Z’). Finally, all the mechanical parameters were transformed from local coordinate to the global coordinate system (XYZ) based on the basic mechanical equation.

3.1.3 | Discretization

In order to calculate the displacement accurately, the elastic-perfectly plastic constitutive relationship with von Mises yield criterion and elastic-plastic constitutive relationship with the Mohr-Coulomb criterion were applied to production casing and cement sheath-formation, respectively. All the mechanical parameters are as shown in the Table 1. Shell elements (shell, S4R) and solid elements (3D stress, C3D8R) were used for meshing the casing and cement sheath-formation. In addition, the structured grid and variable density meshing method were used so as to simplify the modeling, decrease the total nodes and increase the analysis speed.

3.2 | Boundary conditions and simulation steps

3.2.1 | Boundary conditions

(a) Displacement boundary: the displacement and rotation constraint of all the surfaces in the fixed part was set to zero, meanwhile the sliding part was set to that it only could slip along the x-axis negative direction in the 3D system of coordinate, but could not shift or rotate in other directions; (b) Stress boundary: casing pressure was applied on the inner wall, and the far-field stress was applied through the function of the predefined field; (c) Temperature boundary: the temperature of the fracturing fluid was calculated on the basis of Attachment B and applied to the inner surface of the production casing, meanwhile the temperature of the model outside surface was set to a stationary temperature which was equal to the reservoir temperature.
3.2.2 | Simulation steps

At the first step, the initial temperature of the model was set to equal to the reservoir temperature, then the temperature and heat exchange coefficient were applied on the FEM and the temperature field was calculated. Then, stress boundaries were applied to the model, the stress caused by the coupling effect of temperature and pressure was calculated according to thermal elastoplastic theory based on the calculation of temperatures in the first step. The third step, fault slid along the interface between the two faults and casing shear deformation occurred. Finally, the casing inner pressure, sliding distance, mechanical parameters of cement sheath and casing thickness were changed for the purpose of sensitivity study, in order to find a better way to mitigate the influence of fault sliding.

3.3 | Engineering and geological parameters

The geometry and mechanics parameters of a real shale gas well in Simonette, Canada were used to establish the FEM model. The applied horizontal stress was 79 and 56 MPa, and the vertical stress was 62 MPa. The casing internal pressure (downhole pressure, \(P_{in}\)) was 108 MPa according to the engineering practice. The temperature of the horizontal segment in the downhole was 125°. The wellbore diameter was 215.9 mm, and the casing outside diameter was 139.7 mm and its thickness was 9.17 mm; hence, the thickness of the cement sheath between casing and formation was 38.1 mm. The discharge capacity of fracturing fluid was 10 m\(^3\)/min and the fracturing continued for 4 hours in every stage.

4 | RESULTS AND DISCUSSIONS

4.1 | Calculation of the sliding distance

According to the given parameters, the calculated results showed that the critical pore pressure was 84 MPa. During the progress of fracturing, the downhole pressure was as high as 108 MPa, which indicated the strike-slip fault was easy to slide at excessive pore pressure. Microseismic monitoring results demonstrated that strike-slip fault sliding appeared near the position of the research object, as shown in Figure 2. Based on the microseismic monitoring data, the maximum moment magnitude was 3.9, the stress drop was 1 MPa, and the sliding distance was 100.2 mm.

4.2 | Morphological comparison of numerical and measurement results

Figure 3 shows the distributions of production casing displacement after fault sliding. M, M', N', and N were four points in the casing inner surface located at both ends. The plane MM' NN', in which MM' and NN' were the inner diameter of the production casing, was parallel to the sliding direction (Figure 3). For the reason that the reductions of the diameters in the plane MM' NN' were at the maximum, the displacements of line MN and M' N' were calculated to analyze the change of the casing inner diameter.

Figure 4 shows the displacement curves of the line MN and M' N' along the axial, which indicates that the displacements of MN and M' N' are almost the same in the part A and C, but there is a significant difference in part B (from 3 to 5 m). This illustrates that nearly no changes of casing inner diameter occur in part A and C, but part B has the structural distortion. In order to assess the correctness, the measurement result of the deformed part in a special position was selected to compare with the calculation result, the comparison result shows good consistency, as shown in Figure 4.

According to the above analysis, the variation of diameter along the production casing was calculated, as shown in Figure 5. It can be seen that the maximum reduction appeared at the position of sliding interface. According to the calculation result, when the sliding distance is 100.2 mm, the reduction of the casing inner diameter is 27.4 mm (\(\eta = -22.6\%\)). For the reason that the diameter of the original bridge plug is 108 mm, which indicates that it cannot pass through the deformed part.

\[
\eta = \frac{D_{ori} - D_{sli}}{D_{ori}} \times 100\%
\]  

where \(D_{ori}\) represents the original casing inner diameter, mm; \(D_{sli}\) represents the casing inner diameter after fault sliding, mm.

![Variation of diameter and amplitude of variation along the casing](image)
4.3 Sensitivity analysis of casing shear deformation

4.3.1 Influence of sliding distance

Sliding distance has a significant impact on the variation of the production casing inner diameter after fault slipping, as shown in Figure 6. It can be seen that with the increase of the sliding distance, the reduction is increasingly apparent. When the microseismic moment magnitude is more than 3.2 and the stress drop is 1 MPa, the sliding distance is more than 60 mm, and the reduction of casing inner diameter is more than 13 mm. Because of that, the difference between bridge plug outer diameter and casing inner diameter is always lower than 13 mm. It implies that once the moment magnitude is more than 3.2, the stimulation of hydraulic fracturing may be obviously influenced by casing shear deformation. In order to reduce the sliding distance, keeping the designed horizontal segment of well trajectory away from the pre-existing fractures developed area, or be parallel to the natural fracture are conducive to protect the casing integrity are very necessary.

4.4 Influence of casing inner pressure

It is possible that fault sliding appears during or after fracturing, casing inner pressure is different under the two conditions. Figure 7 shows the variation of diameter along the casing under different casing inner pressures, which indicates that casing inner pressure affects the reduction of production casing inner diameter. With the increase of the casing inner pressure, the reduction of the casing inner diameter decreases. The calculation result indicates that maintain a high pressure is beneficial to protect the casing. The reason for this is mainly because casing inner pressure has a dramatic

FIGURE 6 Variation of diameter along the casing under different slip distances

FIGURE 7 Variation of diameter along the casing under different casing inner pressures
impact on the equivalent stiffness of casing string, the higher the casing inner pressure, the higher the equivalent stiffness. But the amplitude of the casing inner diameter variation is <1 mm.

4.5 Influence of casing thickness

Increasing the casing thickness is beneficial to increase the shear resistance strength. Figure 8 shows the variation of diameter along the casing under different casing thicknesses. It can be seen that with the increase of the casing thickness, the reduction decreases obviously. Compared with the reduction when the casing thickness is 9.17 mm (the diameter reduction is 27.7 mm), when the casing thickness increases by 4 mm, the reduction of diameter decreases by 4.8 mm (the diameter reduction is 22.9 mm), which is accounted for 17.3% and indicates that increasing the casing thickness is an effective method to protect the casing integrity.

4.6 Influence of mechanical parameters of the cement sheath

The cement sheath has a protective effect for the production casing, and the mechanical parameters of cement sheath were changed in order to quantify the effect. Figure 9 shows the variation of diameter along the casing under different elasticity modulus of the cement sheath. It can be seen that the higher the elasticity modulus of cement sheath, the more contributions it will make to protect the casing. From Figure 10, it can be seen that with the increase of the Poisson ratio, the reduction of diameter increases, which indicates that the lower Poisson ratio is beneficial to decrease the deformation.

![Figure 8](image8.png)  
**FIGURE 8** Variation of diameter along the casing under different casing thickness

![Figure 9](image9.png)  
**FIGURE 9** Variation of diameter along the casing under different elasticity modulus of cement sheath
Based on the analysis, it can be seen that adjusting the mechanical parameters of the cement sheath is beneficial to protect the casing integrity, but the amplitude of the casing inner diameter variation is less than 2 mm, which indicates that the effects of improvement only play a minor role.

**5 | COMPARISON OF MEASUREMENT AND CALCULATION RESULTS**

This study presented a method to calculate the production casing inner diameter after strike-slip fault sliding. Three other wells were selected to further verify the effectiveness of the model. According to the monitoring results of microseism during multistage fracturing, the moment magnitude was 2.9, 3.2, and 3.3, then the sliding distances and the reduction of production casing inner diameter were calculated based on this study. The measurement and calculation results were compared, as shown in Figure 11. It can be seen that the numerical method in this study has an accuracy up to 85.9%, which indicates that this method can be used as the basis of choosing the soluble bridge plug after casing shear deformation, overcoming the defect that MFC measure was costly as mentioned above.

**6 | CONCLUSIONS**

Casing shear deformation occurred during multistage fracturing in shale gas wells, it caused the increase of stimulation cost and the decrease of shale gas productivity. A new numerical model was developed to stimulate the progress of strike-slip fault sliding and assess the variation of casing inner diameter after fault sliding. The following conclusions are drawn:

**FIGURE 10** Variation of diameter along the casing under different poisson ratios of cement sheath

**FIGURE 11** Comparison of measurement and computed results
1. A numerical model has been developed to analyze the variation of the casing inner diameter. The simulation results showed that: (a) fault slipping caused the reduction of casing inner diameter and the maximum change appeared at the position of interface of the two faults; (b) the casing cross section calculated by numerical model was similar to the shape reflected by MFC measurement result in the special position.

2. Sensitivity analysis was carried out and the influence of sliding distance, casing inner pressure, casing thickness, and mechanical parameters of cement sheath on the reduction of casing inner diameter was analyzed. According to the numerical analysis results, decreasing the sliding distance, maintaining high pressure, increasing casing thickness and increasing the elasticity modulus and decreasing the Poisson ratio of cement sheath were beneficial to decrease the reduction of casing inner diameter.

3. Based on factor sensitivity analysis, it can be found that the most effective method was decreasing the sliding distance. In order to go through this process, keeping the designed horizontal segment of well trajectory keep away from fracture developed area, or be parallel to the natural fracture were very necessary.

ACKNOWLEDGMENTS
This research was financially supported by the Key Program of National Natural Science Foundation of China “Study on failure mechanism and control method of wellbore integrity of shale gas horizontal well” (U1762211), the National Natural Science Funds “Optimum research of non-uniform cluster perforation along the long horizontal section in heterogeneous shale reservoir” (51674272).

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APPENDIX A

Stratification shale shows anisotropic characteristics, which is also known as transverse isotropy. The mechanical characteristics could be expressed in terms of five independent elastic parameters, including $E_h$, $E_v$, $\nu_h$, $\nu_v$, $G_v$, four of them ($E_h$, $E_v$, $\nu_h$, $\nu_v$) can be measured from the mechanical test. A mathematical method for the fifth parameter was proposed in the study of Batugin et al.31

When $O$ is the origin of coordinates, XOZ represents the horizontal bedding plane, XOY and YOZ are all perpendicular to XOZ. Then, $G_v$ can be expressed by the following equation

$$G_v = \frac{E_yE_z}{E_y + E_z + 2\nu_y E_z}$$  \hspace{1cm} (A1)

where $E_h$ and $E_v$ represent the elasticity modulus parallel to and perpendicular to the horizontal bedding plane, GPa, $E_y = E_z = E_v$; $\nu_x$ and $\nu_y$ represent the poisson ratio parallel to and perpendicular to the horizontal bedding plane, GPa; dimensionless, $\nu_{xy} = \nu_{yz} = \nu_v$; $G_v$ represents the shear modulus perpendicular to the horizontal bedding plane, GPa.

During the period of numerical calculation, shear modulus in the three directions are imported into the model:

$$G_v = G_{yz} = G_{xy}$$  \hspace{1cm} (A2)

$$G_h = G_{zx} = \frac{E_h}{2(1+\nu_h)}$$  \hspace{1cm} (A3)

where $G_h$ represents the shear modulus parallel to the horizontal bedding plane, GPa, $G_{zx} = G_h$.

APPENDIX B

In order to conveniently calculate the formation temperature, the values for the temperatures were assumed to be linearly proportional to the true vertical depth.

In the vertical section, the formation temperature could be expressed as follows:

$$T_v = T_{so} + \alpha (z_v - b)$$  \hspace{1cm} (B1)
where $T_f$ is the formation temperature in certain depth, °C; $T_{ss}$ is the land surface temperature, °C; $\alpha$ is the geotemperature gradient, °C/m; $z_f$ is the formation depth, m; $b$ is the benchmark depth, m.

According to the conservation of energy, the heat conduction equation in the wellbore during the fracturing could be expressed as follows:

$$Q \rho_0 C_0 T_{in}^{n+1} - Q \rho_0 C_0 T_{in}^{n+1} + 2\pi r_0 \Delta H_j U \left( T_{in}^{n+1} - T_{in}^{n+1} \right) = \pi r_0^2 \Delta H_j \rho_0 C_0 \frac{T_{in}^{n+1} - T_{in}^{n+1}}{0_{j-\frac{1}{2}} - 0_{j-\frac{1}{2}}} \quad (B2)$$

Then, the heat conduction equation for the solid elements of casing could be expressed as follows:

$$-2\pi r_0 \Delta H_j U \left( T_{in}^{n+1} - T_{in}^{n+1} \right) + 2\pi r_1 \Delta H_j K_1 \frac{T_{in}^{n+1} - T_{in}^{n+1}}{r_1-r_0} = \pi \left( r_1^2 - r_0^2 \right) \Delta H_j \rho_1 C_1 \frac{T_{in}^{n+1} - T_{in}^{n+1}}{0_{j-\frac{1}{2}}} \quad (B4)$$

Then, the heat conduction equations for the solid elements of cement sheath and formation could be expressed as follows:

$$\frac{4\pi r_{i-1} \Delta H_j K_{i-1}}{r_{i-1} - r_{i-2}} T_{in}^{n+1}_j + \left( -\frac{4\pi r_{i-1} \Delta H_j K_{i-1}}{r_{i-1} - r_{i-2}} - \frac{4\pi r_{i} \Delta H_j K_i}{r_{i+1} - r_{i-1}} \right) \frac{T_{in}^{n+1}_j - T_{in}^{n+1}_j}{r_{i+1} - r_{i-1}} = \frac{4\pi r_{i} \Delta H_j K_i}{r_{i+1} - r_{i-1}} \frac{T_{in}^{n+1}_j - T_{in}^{n+1}_j}{0_{j-\frac{1}{2}}} \quad (B5)$$

where $Q$ is the discharge capacity of fracturing fluid, m³/min; $U$ is the convective heat transfer coefficient between the fracturing fluid and casing wall, w/(m²·°C); $\Delta H_j$ is the height of the control unit body (m); $\rho_i$ is the density, kg/m³; $C_i$ is the specific heat, J/(kg·°C); $r_i$ is the radius, m. when $i = 0$, 1 ≤ $i < m$, $m$ ≤ $i < n$, $n$ ≤ $i < o$, the meshing grids represent the fracturing fluid, production casing, cement sheath, and formation.

When the fracturing fluid was pumped into the wellbore downhole with high discharge, it was in the state of turbulence. The convective heat transfer coefficient between the casing and fluid can be calculated by using the Marshall model shown [30].

$$U = \frac{S_k K_0}{D} = 0.0107 K_0 \frac{D}{D_{eff}} \left[ \rho_0 D_{eff} \frac{4Q}{\pi D^2} \right] \left[ K \left( \frac{3n+1}{4} \right) ^{n-1} \left( \frac{32Q}{\pi D^2} \right) ^{n-1} \right] ^{0.67} K_{con} \left( \frac{3n+1}{4n} \right) ^{n-1} \left( \frac{32Q}{\pi D^2} \right) ^{n-1} \frac{C_0}{K_0} ^{0.33} \quad (B6)$$

where $S_k$ is the Stanton number, dimensionless; $K_0$ is the heat conductivity coefficient, w/(m·°C); $D$ is the casing diameter, m; $D_{eff}$ is the equivalent diameter of casing, m; $n$ is the liquidity index, dimensionless; $K_{con}$ is the consistency, Pa/sⁿ.

The temperature governing equations in the inclined and horizontal section were essentially the same as in the vertical section, but the boundary conditions changed.

In the inclined section, it was assumed that the whole section was a quadrant and divided equally into $N$ equal parts, and then, the vertical depth of any one of them could be expressed as follows:

$$z_{in-k} = z_v + R \sin \left( (k-1) \frac{\pi}{2N} + \frac{\pi}{4N} \right) \quad (B7)$$

where $z_{in-k}$ is the vertical depth of the part $k$, m; $R$ is the radius of the quadrant, m.

Then, the temperature boundary in the inclined section could be calculated according the geotemperature gradient.

In the horizontal section, the wellbore continued to extend but the formation temperature was independent of the well depth. The formation temperature could be expressed as follows:
where $T_{ho}$ is the formation temperature in the horizontal section, °C.

According to the equations from B1 to B8, the temperature variation in the casing inner surface with time was calculated and could be expressed as follows:

$$T_{ho} = T_{su} + a \left( z_v + z_{in} - b \right)$$  \hfill (B8)

$$T_Q = f(Q, g(z, d), t)$$  \hfill (B9)

where $z$ is the vertical depth of the well, m; $d$ is the measured depth of the well. $g(z, d)$ is any location in the wellbore decided by the vertical and measured depth of the well.