DOI 10.1007/s10553-022-01460-x
Chemistry and Technology of Fuels and Oils, Vol. 58, No.5, November, 2022 (Russian Original No.5, September–October, 2022)

INNOVATIVE TECHNOLOGIES OF OIL AND GAS

EFFECT OF POROELASTICITY ON THE INTEGRITY OF CEMENT SHEATH IN HEAVY OIL WELLS

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Integrity of cement sheath is critical for safe and effective operation of heavy oil wells. The cement sheath has been generally treated as elastic solid in existing models for integrity analysis. However, it has been evidenced by some recent research findings that cement is essentially a porous solid, and thus poroelasticity effect may be remarkable. In this paper, we established a transient poro-thermo-mechanical coupling finite element model and investigated the pore pressure and stress evolution within the cement sheath during the heat injection process of heavy oil wells, with the emphasis on clarifying the effect of poroelasticity of cement and formation on the integrity of cement sheath. It is found that temperature rise during heat injection results in considerable pore pressure increase and thus greatly affects the stress distribution within the cement sheath. For the cement sheath between the casing and the rock formation, the pore pressure within the cement sheath decreases gradually with time due to fluid diffusion into the formation. In contrast, the high pore pressure remains almost constant within the cement sheath between two casings, resulting in tensile effective stress within the cement sheath and raise a high risk of failure, which cannot be predicted by existing elasticity model.

Keywords: cement sheath integrity, poro-thermo-mechanical model, heat injection.

Introduction

Heavy oil is an important unconventional resource with wide distribution and rich reserves. Except for Antarctica, heavy oil reservoirs are found everywhere. In addition, the global reserves of heavy oil resources can reach 100 billion tons, much more than the reserves of conventional oil reservoirs [1, 2].

Thermal recovery technology adopts a relatively simple method of heavy oil heating and viscosity reduction, which is one of the most successful technologies for heavy oil reservoir development and has been widely used [3]. Steam injection thermal recovery is the main method to recover heavy oil at present [4]. However, gas channeling generally occurs in heavy oil wells because of this technology [5]. Under the conditions of heat injection in thermal recovery Wells, the integrity of cement and

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casing is severely challenged by the pressure and the temperature, and the failure of cement integrity occurs in major oil fields all over the world.

In recent years, scholars have carried out a great deal of research and exploration on cement integrity. Great achievements have been made in establishing the casing-cement-formation combination model and numerical calculation of cement annulus integrity by using finite element theory. Thiercelin et al. [6] assumed that casing, cement, and rock were thermoelastic media and established a stress calculation method for the casing-cement-formation assembly under temperature and pressure changes. Deng Jingen et al. [7] established a two-dimensional plane axis-symmetric and plane strain finite element model and analyzed the deformation characteristics of casing subjected to uniform and non-uniform external extrusion load under the action of cement sheath by using the finite element model. Bosma M. et al. [8] used the finite element method to analyze the regularity of shear failure, tensile fracture, and formation of micro-annulus caused by changes in downhole temperature and pressure conditions. Li Jun et al. [9] established the finite element model of the casing-cement-formation combined system based on the finite element theory and used MSC. Marc software to analyze the influence of elastic modulus and Poisson's ratio of cement and different formations around the well site on casing load. Gray, K. etc. [10] put forward that numerical simulation should be considered when integrating the well history of a building, in order to get more accurate results. Using finite element method to establish casing. Zhang Jingfu et al. [11] established the plane strain model of casing-cement-formation combined system with finite element method and found that cement stones with low elastic modulus, strong tensile capacity, appropriate yield strength, and high interface bonding strength have higher bearing capacity. Raoof, Jesus, et al. [12, 13] established a numerical model to analyze the integrity status of cement sheath under different cementing quality conditions based on considering the coupling effect of temperature and pressure.

However, most of the existing casing-cement-formation combination models are always based on elasticity, without considering the effect of the poroelasticity of cement and formation on the stress state of the cement, which is inconsistent with the actual working conditions. Recently, studies have shown that cement should be regarded as a porous medium material rather than a linear elastic material [14]. As porous media materials, cement and rocks have pore fluid in actual conditions. The change of temperature during heat injection may have a great effect on the pore pressure in the cement sheath. Therefore, this paper, by using a numerical simulation method to establish comprehensive consideration of the poroelasticity, pressure, and temperature of the casing-cement-formation coupling model, and compared with the traditional model which only considers temperature and pressure load in the casing, and research the effect of pore pressure on cement stress. The research on the mechanical integrity of cement sheath is further improved and supplemented, and the theoretical basis and suggestions are provided for on-site heavy oil Wells.

Finite element analysis method for casing-cement-formation coupling model with poroelasticity

The Poro-thermo-mechanical coupling model was solved by the general nonlinear finite element software package ABAQUS. The stress and temperature distribution in the cement sheath are calculated by taking the casing-cement-formation assembly with unit thickness perpendicular to the borehole axis as the research object. In the transient Poro-thermo-mechanical coupling analysis, the porous media was regarded as multiphase material, and the effective stress principle was used to describe its behavior. Coupled Poro-thermo-mechanical elements are used to simulate heat conduction in soil skeleton and pore fluid, ABAQUS solves the heat transfer equation in a fully coupled manner with the continuity equation and the mechanical equilibrium equations. The continuity equation and the heat transfer equation are integrated using a backward difference operator. Then pore pressure distribution, effective stress distribution, and temperature distribution can be obtained. It is assumed that the material of the casing in the composite body is a mean isotropic linear elastic solid, and the cement and formation are pore medium materials. The interface between casing and cement and the interface between cement and formation is continuous. The axial direction of the combination satisfies the plane strain model. Constraint formation boundary displacement, in-situ stress, and pore pressure as the initial stress, pressure, and temperature inside the casing as the external load. In this paper, a thermal recovery well of heavy oil was selected as the research object. Considering the influence of pore pressure in the formation and cement sheath, the stress and temperature distribution of cement sheath were calculated under the condition of Poro-thermo-mechanical complete coupling.

Table 1. Geometric dimensions of the casing-cement-formation system and double casing-cement-formation system

Component	Inner radius (mm)
Casing-cement-formation system	
Casing	57.15
Cement	69.85
Formation	107.95
Double casing-cement-formation system	
Casing1(2)	59.31 (111.19)
Cement1(2)	69.85 (122.24)
Formation	155.6

Model setup and input parameters

Taking the representative parameters of heavy oil well as the research object, the stress state simulation of cement sheath based on pore pressure is carried out, and the effect of pore pressure in the formation and cement on the stress distribution of cement is revealed. **Table 1** show the geometric dimensions of the single \double casing-cement-formation model. **Fig. 1** shows the corresponding geometric model.

The depth of the production interval is approximately 2040 m. The uniform ground stress σ is 41.49 MPa. The initial pore pressure is set as 20.2 MPa in the formation and cement sheath in model 1, 20.2 MPa in the formation and cement in contact with the formation in model 2, and 0 MPa in the cement sheath between two casing layers. The input parameters used in the simulation are shown in **Table 2**. The temperature of the wellbore rose to 350°C for 3000s from 58.5°C, and the internal pressure within the casing p_w is 16.68 MPa. The other numerical model without the poroelasticity is established, the parameter settings are the same

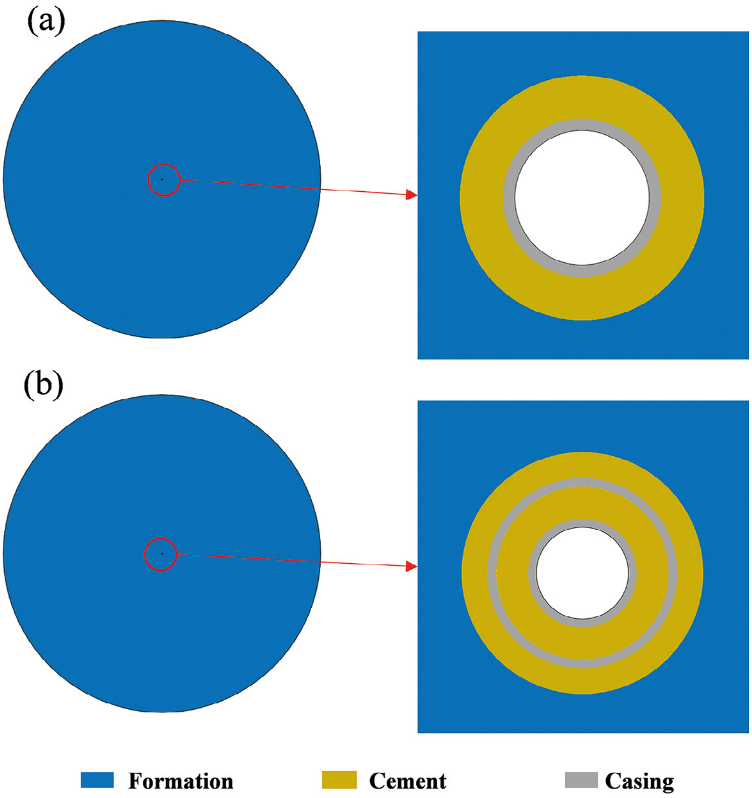

Fig. 1. Geometry of the model for (a) single (b) double casing-cement-formation

Table 2. Input parameters for the modeling conducted in this paper

Component	Casing	Cement	Formation	Formation fluid
Young’s modulus (GPa)	200	10	30	–
Poisson’s ratio	0.3	0.2	0.2	–
Thermal expansion (10^{-6} /°C)	12	10	11.6	66
Density (kg/m^3)	7870	2200	2500	1000
Specific heat (J/(kg·°C))	460	1000	2000	2000
heat conduction (W/(m·K))	40	0.34	2.65	2.65
Permeability (mD)	–	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-5}$	–
Porosity	–	0.25	0.06	–
Poisson's ratio without discharge	–	0.281	0.35	–
Biot coefficient	–	0.578	0.851	–
Fluid viscosity (Pa·s)	–	0.001	0.001	–
Skempton	–	0.547	0.653	–
Shear modulus (GPa)	–	4.17	12.5	–
Solid–phase volume modulus (GPa)	–	13.165	111.86	–
Fluid volume modulus (GPa)	–	2.3774	2.1668	–

as the model above except for the parameters of the poroelasticity. Then get the stress distribution, pore pressure, and temperature distribution of cement after 30 days of heat injection.

Results and discussions

The distribution of effective stress, temperature, and pore pressure in casing-cement-formation at the final moment is shown in **Fig. 2**, and the corresponding total radial stress, total hoop stress, and pore pressure are shown in **Fig. 3**. At the final moment, the total radial stress of cement is about –77…–66 MPa with pore pressure and about –64…–48 MPa without pore pressure, and the total hoop stress is about -86MPa with pore pressure and about –12MPa without pore pressure, and the pore pressure is about

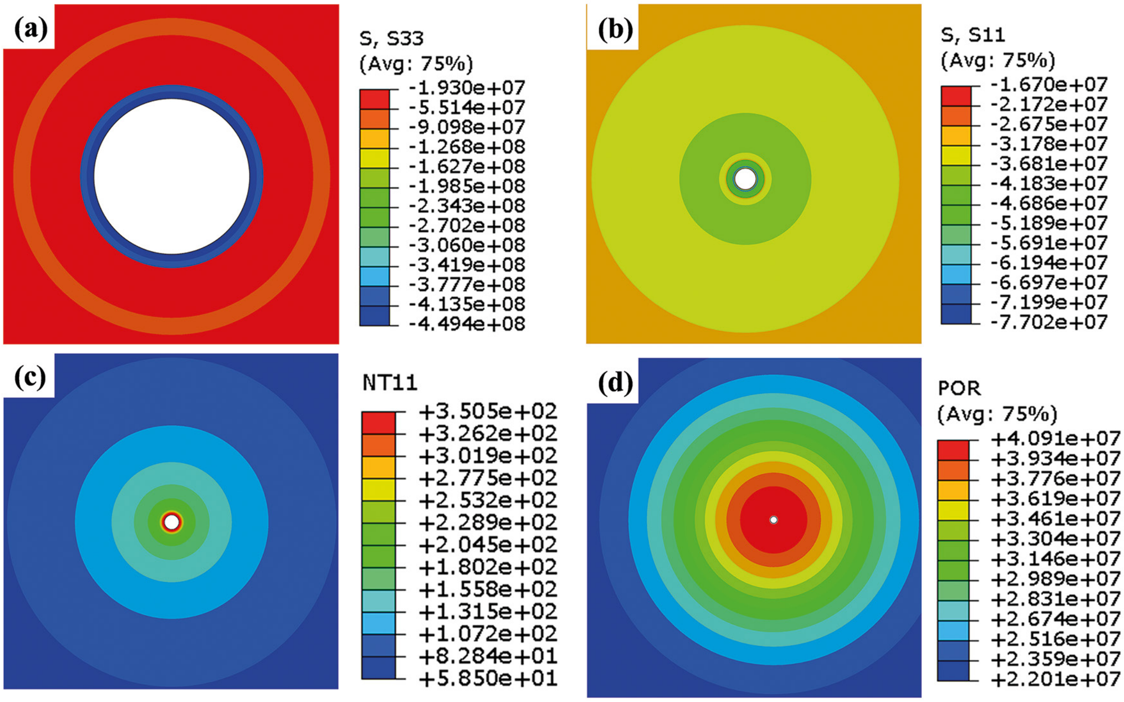

Fig. 2. (a) Radial effective stress (b) hoop effective stress and (c) temperature (d) pore pressure distribution at the final moment (1casing with pore pressure)

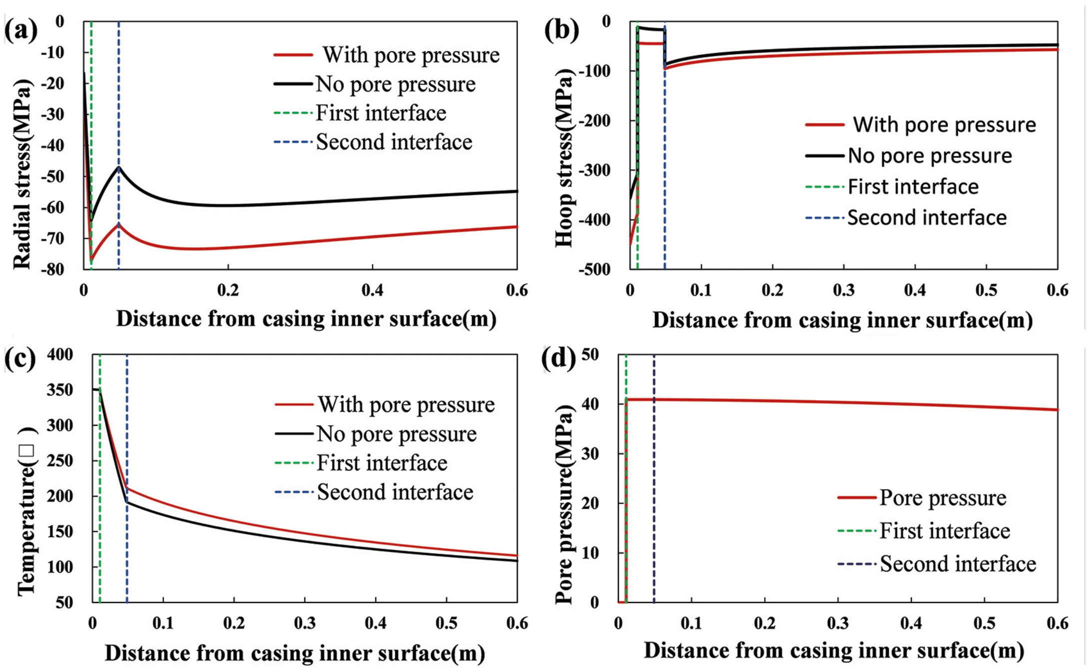

Fig. 3. (a) Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with time of the final moment (1 casing)

40.9 MPa. When pore pressure is taken into account, the cement is subjected to greater compressive stress at the final moment, and there's almost no difference in temperature. The relation between total stress and effective stress is shown as follows:

$$\sigma_p = \sigma'_p + \partial p_f ,$$

σ_p is total stress, σ'_p is effective stress, ∂ is biot coefficient, p_f is pore pressure.

Fig. 4 shows the first interface total stress and temperature evolution over time, after the temperature rise (3000s), the radial stress reaches –78 MPa with pore pressure and –61 MPa without pore pressure, The hoop stress is about –52 MPa with pore

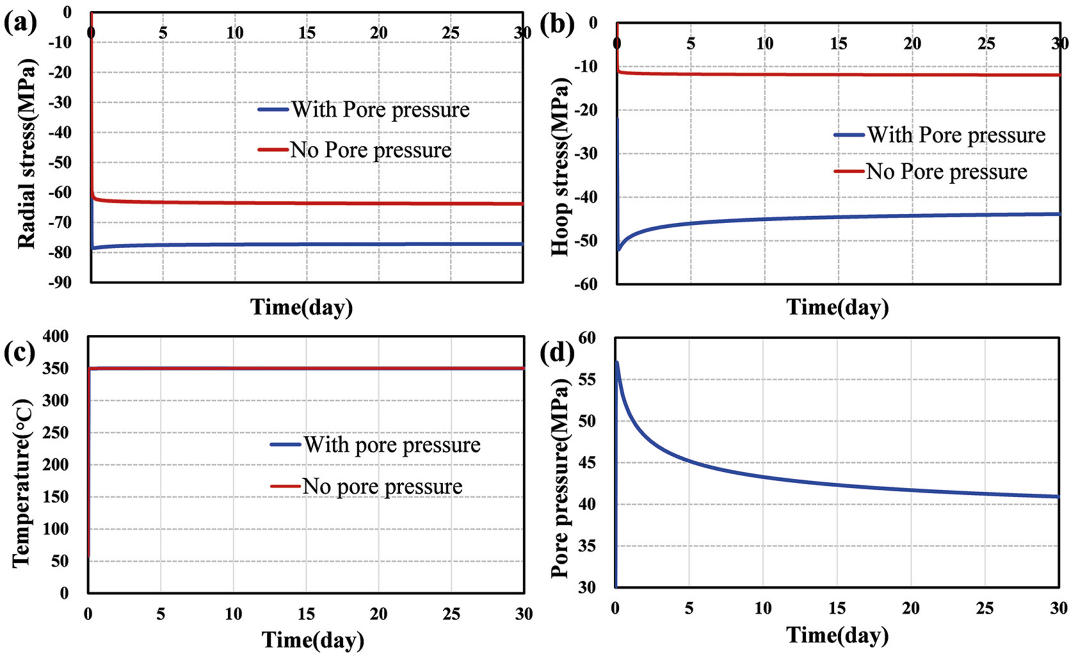

Fig. 4. (a)Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with the time of the first interface (1casing)

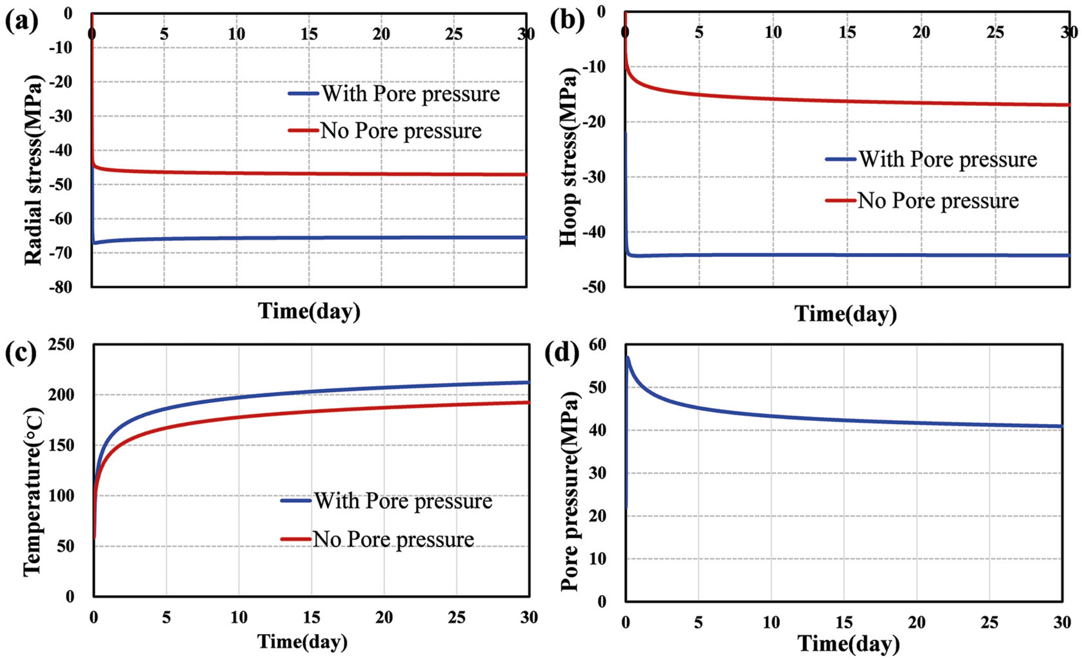

Fig. 5. (a) Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with the time of the second interface (1casing)

pressure and –11 MPa without pore pressure. Then, under the action of high temperature, the compressive stress in the cement continues to increase slowly. When the temperature increases, the pore pressure increases rapidly, up to 57 MPa. When the temperature stabilizes, the fluid in the cement diffuses to the formation and the pore pressure decreased to about 41 MPa after 30 days. The temperature change of this interface is similar to the temperature change of the casing.

Fig. 5 shows the second interface total stress and temperature evolution over time, after the temperature rise(3000s), the radial stress reaches –67 MPa with pore pressure and –45 MPa without pore pressure, The hoop stress is about –44 MPa with pore pressure and –11 MPa without pore pressure, then changed little. The temperature is always in the heating stage, and the temperature rises faster when the pore pressure is considered. The evolution of the pore pressure is consistent with that of the first interface.

Considering that the actual borehole structure is mostly a multi-layer casing-cement combination, the stress evolution of the multi-layer casing-cement-formation combination with time is further studied. The distribution of effective stress and pore pressure in double casing-cement-formation at the final moment is shown in **Fig. 6**, and the total radial stress, total hoop stress, and pore pressure are shown in **Fig. 7**. At the final moment, the total radial stress of cement1 is about –70…–66 MPa with pore pressure and about –44…–33 MPa without pore pressure, the total hoop stress is about –50 MPa with pore pressure and about –7 MPa without pore pressure, and the pore pressure is about 133 MPa. the total radial stress of cement2 is about –72…–65 MPa with pore pressure and about –51…–43 MPa without pore pressure, the total hoop stress is about –38 MPa with pore pressure and about –13 MPa without pore pressure, and the pore pressure is about –37 MPa. Due to the first and second interfaces being between two casings and do not flow with formation fluids, the temperature increases and the pore pressure is very high and difficult to drain after 30 days, while the third and fourth interfaces flow with formation fluids and the pore pressure is low. When pore pressure is taken into account, the cement is subjected to greater compressive stress at the final moment, and the temperature has little difference. It is the same as the single casing model.

Fig. 8 shows the evolution of total stress and temperature at the first interface over time. As the temperature increases, the compressive stress in the cement increases rapidly, and the compressive stress is greater when pore pressure is considered. With the temperature rise (3000s), the radial stress reaches –73MPa with pore pressure and –53 MPa without pore pressure, The hoop stress is about –54 MPa with pore pressure and –8 MPa without pore pressure. The difference in temperature between the two casings leads to the further increase of the compressive stress in the cement and then decreases with the decrease in temperature

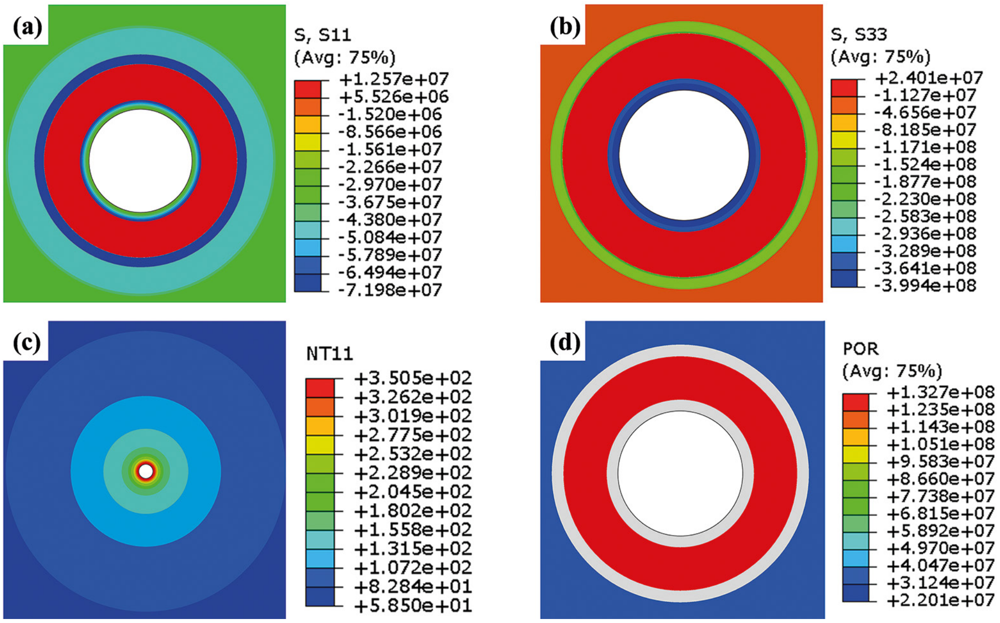

Fig. 6. (a) Radial effective stress (b) hoop effective stress (c) temperature and (d) pore pressure distribution at the final moment (2 casing with pore pressure)

difference. The temperature has a significant effect on pore pressure. Pore pressure increases with temperature increases, and because the cement sheath is located between two casing layers, pore fluid is difficult to discharge, up to 130 MPa.

Fig.9 shows the evolution of total stress and temperature at the second interface over time. The variation of stress and temperature at this interface is similar to that at the first interface. after the temperature rise (3000s), the radial stress reaches –64 MPa with pore pressure and –36 MPa without pore pressure, The hoop stress is about –46 MPa with pore pressure and –7 MPa without pore pressure after changed little. Due to the rapid transfer of pore pressure in the cement sheath, the pore pressure at this interface is the same as that at the first interface. The temperature at the interface is always in a rising stage and finally rises to about 230°C.

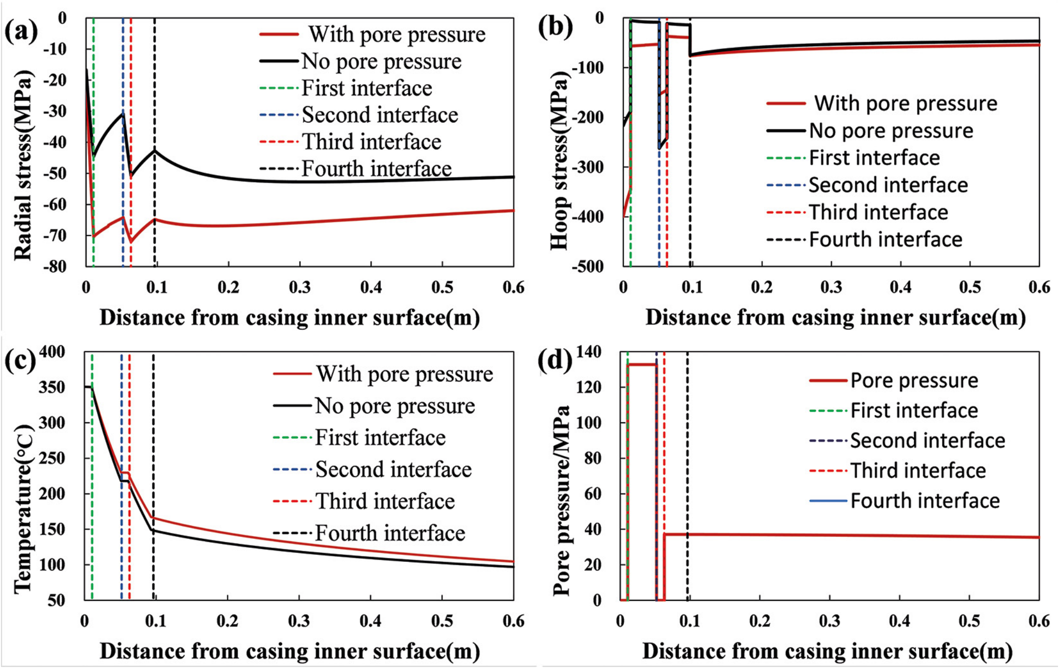

Fig. 7. (a) Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with time of the final moment (2 casing)

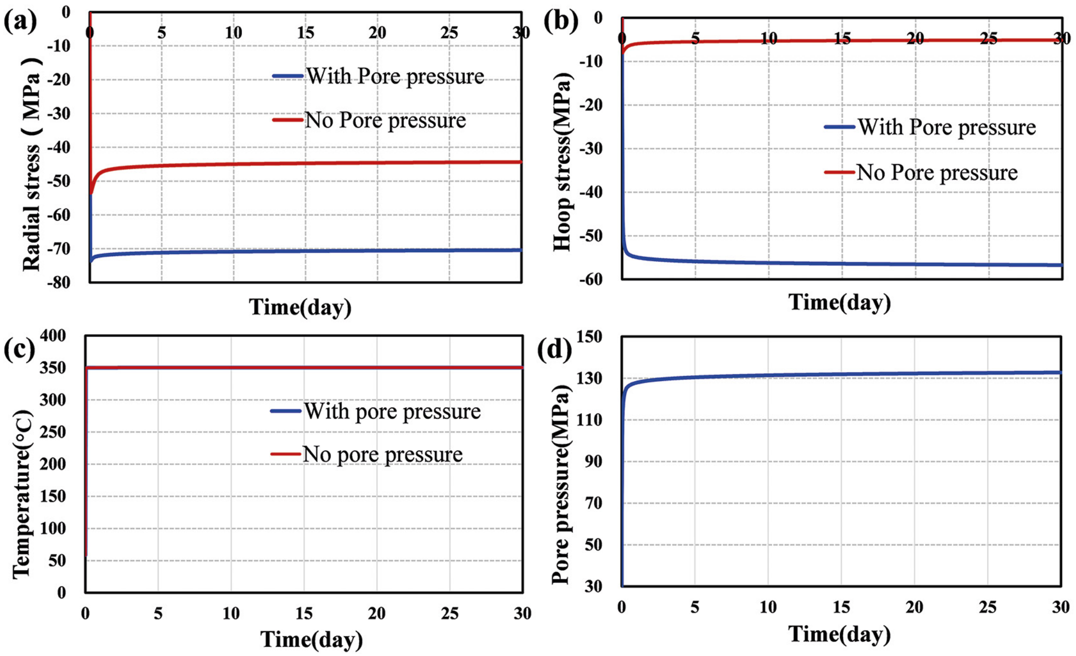

Fig. 8. (a)Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with the time of the first interface (2 casing)

Fig. 10 shows the evolution of total stress and temperature at the third interface over time. after the temperature rise (3000s), the radial stress reaches –61 MPa with pore pressure and –38 MPa without pore pressure, The hoop stress is about –35 MPa with pore pressure and –7.5 MPa without pore pressure. Then, under the action of high temperature, the compressive stress in the cement continues to increase slowly. When the temperature increases, the pore pressure increases rapidly. When the temperature stabilizes, the fluid in the cement diffuses to the formation and the pore pressure decreases. The temperature at the interface is always in a rising stage and finally rises to about 230°C.

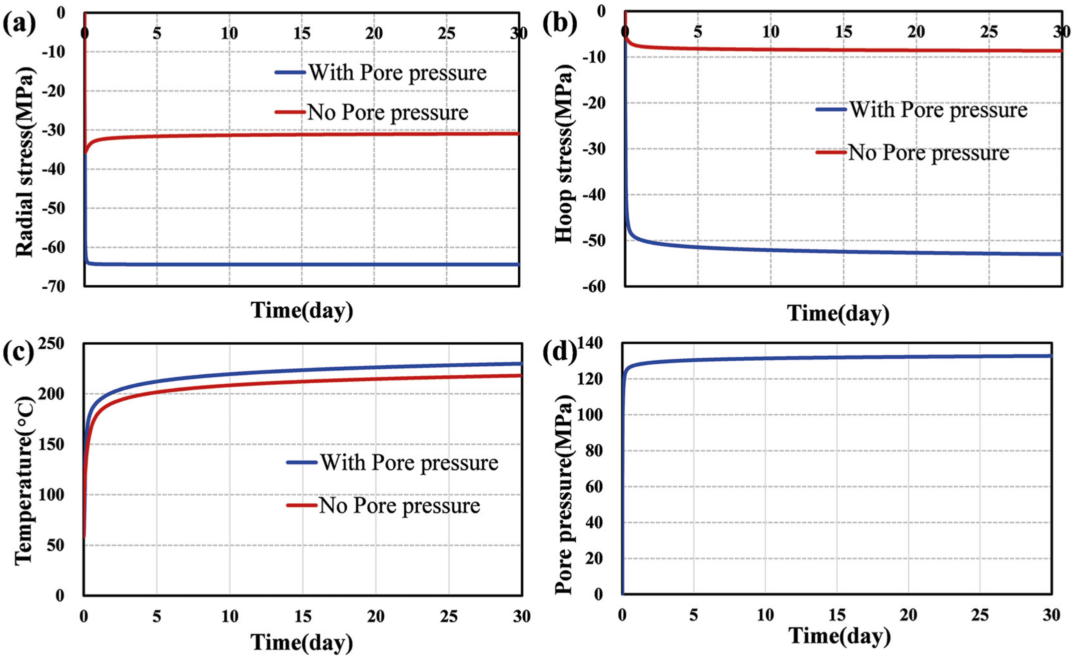

Fig. 9. (a)Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with the time of the first interface (2 casing)

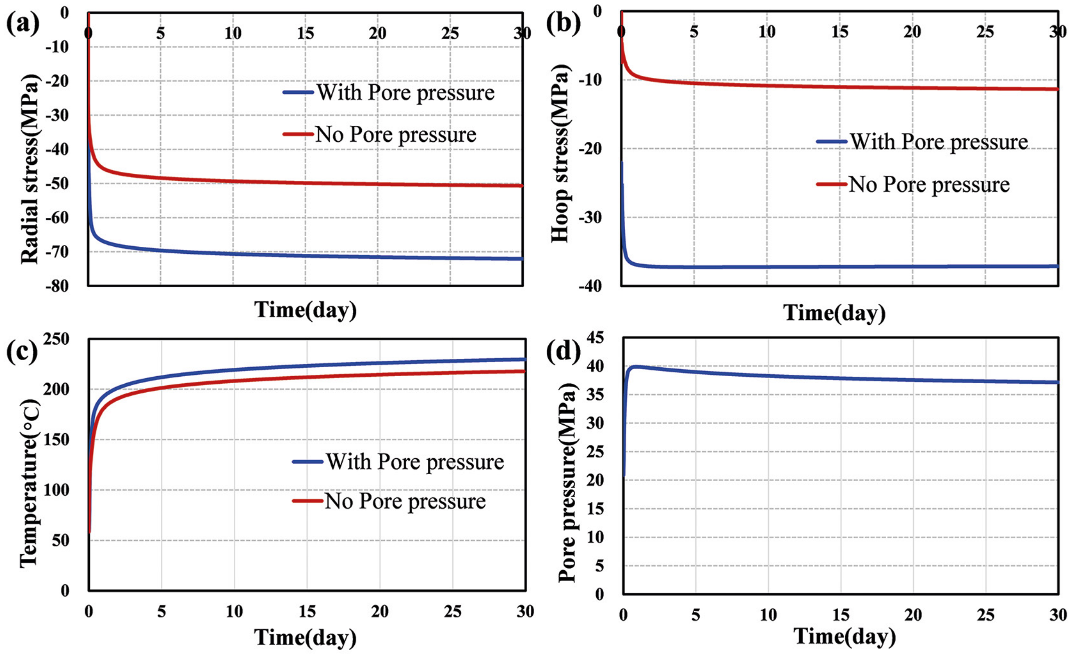

Fig. 10. (a)Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with time of the third interface (2 casing)

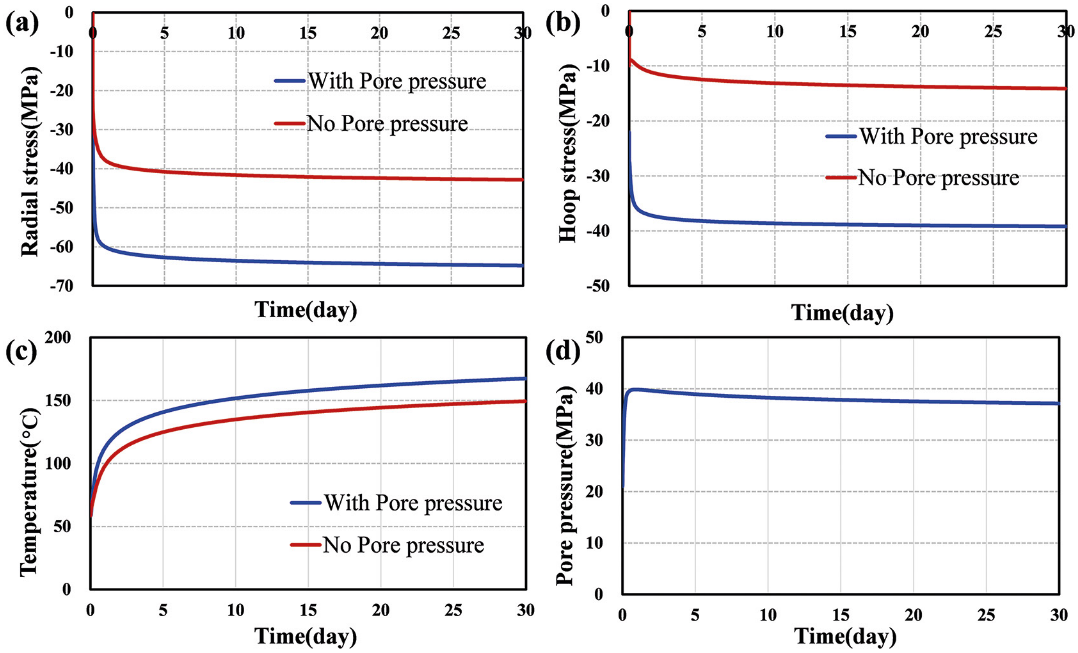

Fig. 11. (a) Radial total stress (b) hoop total stress (c) temperature and (d) pore pressure changes with the time of the fourth interface (2 casing)

Fig. 11 shows the evolution of total stress and temperature at the fourth interface over time. The temperature of the interface is rising all the time, and the final temperature is about 150°C. The variation of radial/ hoop stress and pore pressure is consistent with that of the third interface. but the variation range is smaller than that at the first interface.

Conclusions

In this paper, a numerical model of casing-cement-formation with Poro-thermo-mechanical coupling is established to investigate and explore the stress and temperature distribution of cement sheath under heat injection conditions of heavy oil is calculated, the following conclusions could be drawn from the investigations.

1. Because the effect of the pore fluid in cement and formation is considered, the model can better simulate the stress and temperature change of cement sheath during heat injection process, and the calculated stress state of cement is more consistent with the actual working condition, which can more accurately predict the possible failure mode of cement sheath.
2. Temperature has a great effect on the pore pressure. With the increase in temperature, the pore pressure increases. Because the first and second interfaces are between two casings and do not flow with formation fluids, the temperature increases generate high pore pressure which remains unchanged and has a high risk of failure. While the third and fourth interfaces flow with formation fluids, resulting in a small increase in pore pressure, and then decreasing slowly with pore fluid replenishment.
3. When poroelasticity is considered, the temperature propagation rate of the cement sheath is faster, and the risk of tensile failure is reduced. The compressive stress in the cement increases slowly with time under continuous loading at high temperatures.
4. In the double casing model, the cement sheath between two casings is not only affected by the compressive stress caused by high temperature, but also by the extrusion of two casings, which has a high risk of failure.

Acknowledgement

The authors wish to acknowledge the financial support from the Petrochina Xinjiang Oilfield Company (Engineering Technology Institute).

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