Experimental investigation of frost heave force on tubing and casing

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Abstract. Currently, CO₂ injection is mainly used to rejuvenate oil reservoirs as a tertiary oil recovery technology. During the cryogenic CO₂ injection process, when the temperature drops below the freezing point of water, the volume expansion caused by the freezing of the water in the tubing and casing annulus generates a frost heave force. This additional force increases the risk of tubing fracture and shortens the life of the well. Therefore, in this paper, a laboratory experiment is carried out to analyse the characteristics of tubing and casing stress under the effect of a frost heave force. The results show that the frost heave force in the annulus squeezes the tubing and casing into an ellipse during the freezing process and that the strength of the frost heave force is approximately equivalent to the internal pressure of 104 MPa in a thin-walled cylinder pressure vessel of the same size. The experimental results explain the tubing and casing failure mechanism with the effect of frost heave force and provide a theoretical basis for providing a solution to improve the service life of tubing and casing in a cryogenic CO₂ injection well.

1. Introduction

The negative impacts of global warming and climate change have necessitated worldwide efforts to reduce CO₂ emissions into the atmosphere [1-2]. Among various approaches, carbon capture, utilization and storage (CCUS) can efficiently and safely sequester large amounts of CO₂ from major emission sources. Meanwhile, CO₂ injection or storage in mature or partially depleted oil reservoirs has the benefit of improved oil recovery, providing an offset to the cost of storing CO₂ [3]. Therefore, to achieve efficient and safe CO₂ injection into a wellbore, several typical oil wells were selected for preliminary exploratory testing in the Taizhou Jiangsu Oilfield. However, the test results were not satisfactory, and the tubing and casing of some test wells were damaged to varying degrees. Several typical tubing and casing failure conditions from the abnormally working test wells are shown in Fig. 1.

Fig. 1 Failure state of tubing in the CO₂ injection wells
It can be clearly seen that the tubing of Wells H3-5 and S5-4 cracked and leaked. Meanwhile, the casing of Wells H3-5 and S5-4 exhibit leakage points at depths of 130 m and 177 m, respectively. In oil and gas fields, well safety is always a top priority. The failure of tubing and casing poses a threat to well safety during production and severely limits the promotion and application of CO2 enhanced oil recovery technology. Therefore, it is of great importance to explore the failure mechanism of tubing and casing under the effect of frost heave force.

2. Experiment scheme
The simulated wellbore consists of tubing, casing and upper and lower end covers, as shown in Fig. 2.

![Fig. 2 Schematic diagram of the laboratory experiment](image)

The outer diameters of tubing and casing are 73.02mm and 139.7mm, while the wall thicknesses of tubing and casing are 5.51mm and 9.17mm, respectively. The total length of tubing and casing is 11500mm. Water represents the wellbore annulus liquid. In this paper, the characteristics of frost heave force are analysed by measuring the stress on the outer wall of the casing. To elucidate the characteristics of the variation in stress with time during the cooling process, an electrical resistance strain gauge system is introduced in the stress measurement experiment [4]. There are three test points on the outside of the casing, namely, the upper test point, the middle test point and the lower test point. A freezing cabinet is used as the temperature control and cooling system. The data acquisition system DHDAS is connected to a computer. The data are automatically collected during the testing process.

3. Results and discussion

3.1 Cooling process
The experimental results of the characteristics of the variation in stress with time during the cooling process are shown in Fig. 3. The variation in stress with time during the cooling process can be divided into four stages: the initial cooling stage (ICS), freezing process stage (FPS), further cooling stage (FCS), and temperature stabilization stage (TSS).
Fig. 3 Characteristics of the variation in the stress with time during the cooling process

The first stage (ICS) lasts approximately 5.9 hours. During this stage, the temperature of the device is reduced from room temperature (20°C) to the freezing point. The water in the annulus remains in the liquid phase, and its temperature continuously decreases to the equilibrium phase change temperature [5]. Meanwhile, the stress at the test points becomes more negative as the freezing cabinet temperature decreases. The negative stress is a compressive stress. Therefore, during this stage, the tubing and casing are affected by cooling shrinkage. The maximum compressive stress of the test points reaches 32 MPa.

The second stage (FPS) lasts approximately 6.6 hours. During this stage, water changes from a liquid phase to a solid phase. Water does not turn into a solid phase instantaneously but forms crystals that grow into ice [6]. The first process is supercooling, which drives rapid kinetic crystal growth from the crystal nuclei [5]. There is an abrupt temperature rise as this growth liberates the latent heat of fusion. This process is terminated when the supercooling is exhausted and the liquid has reached its equilibrium freezing temperature. The second process is freezing, where further growth of the crystal is governed by the rate of heat transfer to the environment from the liquid. This process continues until the liquid is completely frozen. As the temperature is further reduced, the liquid slowly freezes. The original annulus space can no longer freely store the expanded volume of newly generated ice as more water freezes. Therefore, the frost heave force on the inner wall of the annular space is caused by this incremental volume. The annulus pressure increases as the ice molecules squeeze the tubing and casing, which reduces the freezing point temperature accordingly [7]. Therefore, this stage lasts for a while.

The second stage starts when the stress of the test point reaches the maximum compressive stress. Then, the positive (tensile) stress increases linearly with increasing frost heave force. The middle test point stress is smaller than those of the test points at the ends. This can be explained by the lack of support outside the experimental device, so the upper and lower ends can be approximated as free ends. Therefore, it is easier to generate larger stresses at the ends. The maximum tensile stress is observed at the lower test point, and its value reaches 550 Mpa.

At time $h_b$ in the experimental test, a distinct sound was heard, and the stresses at the test points instantly dropped from the maximum to near 0 Mpa. This means that the frost heave force acting on the tubing and casing suddenly and completely releases at this moment. One explanation of the release of frost heave force may be that some of the water and/or ice migrated out of the annulus at this time because the amount of water in the annulus after the experiment was less than before the experiment started. The experimental device was disassembled after the experiment was completed, and the middle section of the tubing was compressed into an ellipse (see Fig. 4). Due to the elliptical deformation of the casing, the original joint is no longer completely sealed, which provides an outlet for water and/or ice to migrate out of the annulus.
The third stage (FCS) lasts approximately 7.7 hours. It is an ice cooling stage, where the ice temperature is reduced to near the preset temperature (-20°C). The annulus liquid has completely transformed into a solid. Similar to the first stage, in this stage, as the temperature continues to decrease, the tubing and casing are only affected by cooling shrinkage. Therefore, the stress at the test points becomes more negative again. The maximum compressive stress of the test points is 86 Mpa in this stage.

The fourth stage (TSS) lasts approximately 20.1 hours. During this stage, the temperature of the freezing cabinet is reduced to the preset temperature (-20°C) and then stabilized around this temperature. Therefore, the stress at each test point does not change because each part of the experimental device remains in equilibrium.

### 3.2 Heating process

When the cooling process is completed, the freezing cabinet is turned off and opened, and the experimental device is naturally warmed to room temperature. Similarly, the characteristics of the variation in the stress of the heating process can be divided into four stages: temperature stabilization stage (TSS), temperature rise stage before thawing (TRSB), thawing stage (TS), and temperature rise stage after thawing (TRSA); see Fig. 5.

![Fig. 4 The tubing state after the experiment](image-url)

![Fig. 5 Characteristics of the variation in the stress with time during the heating process](image-url)
The first stage (TSS) lasts approximately 20.1 hours. This stage begins at the end of the fourth stage of the cooling process. Since the temperature of the freezing cabinet is stable around the present temperature, the stress remains in equilibrium.

The second stage (TRSB) lasts approximately 0.8 hours. As the freezing cabinet is shut down and the experimental device is exposed to the atmosphere, the temperature of the experimental device recovers to room temperature. It is obvious that the temperature variation rate during heating process is greater than that during the cooling process, as there is a higher average heat transfer temperature difference with the atmosphere. When the ice in the annulus is heated from -20°C to the freezing point, the experimental device is in a thermal expansion state. Therefore, the stress of the test points increases from the initial negative value to the positive value at this stage, indicating that the stress generated at this time is tensile stress.

The third stage (TS) lasts approximately 0.7 hours. Just before the experiment temperature rises to the freezing point, the stress reaches the maximum tensile stress. The maximum tensile stress is observed at the lower test point, and its value reaches approximately 80 Mpa. As the temperature continues to rise, the ice in the annulus thaws, and the frost heave force on the tubing and casing gradually releases. Therefore, the stress decreases and approaches zero.

The fourth stage (TRSA) lasts approximately 9.2 hours. When the ice in the annulus completely thaws into water, the stress of the experimental device is completely released. As the tubing and casing were deformed at the end of the second stage of the cooling process, the annulus space was expanded by the frost heave force, and some of the water and/or ice migrated out of the annulus. Thus, there is enough space for the thermal expansion of water when the temperature continues to rise, and the test point stress basically does not change during this stage.

3.3 Failure analysis
Based on the aforementioned tensile testing results of the material, it is known that the yield strength of the N80 material is between 671 Mpa and 692 Mpa in the temperature range of 20°C to -20°C. The maximum comprehensive stress tested on the outer wall of the casing is 550 Mpa, which is less than the yield strength of this material, but the experimental casing and tubing still underwent plastic deformation and failure. This finding can be explained as follows:

The outer diameter of the casing is 139.7 mm, and the wall thickness is 9.17 mm. Since the ratio of the outer diameter to the inner diameter is less than 1.2, the casing can be assumed to be a cylindrical thin-walled pressure vessel. Lamé’s solution, as the standard in the analytical study of pressure vessels and press fits, is adopted in this paper [8]. The stress distribution of the pressure vessel of the same size under the internal pressure of 104 Mpa can be obtained as follows: the maximum circumferential stress on the inner wall is 743 Mpa, the minimum circumferential stress on the outer wall is 639 Mpa, the axial tensile stress of the whole wall is 319 Mpa, the maximum radial stress on the inner wall is -104 Mpa, and the minimum radial pressure on the outer wall is 0 Mpa. Then, the elastic failure criterion is adopted in this paper, and in three-dimensional principal stress space, the von Mises condition can be expressed as:

\[
\sigma_{\text{von}} = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]}
\]  

(1)

where \(\sigma_{\text{von}}\) denotes the von Mises equivalent stress, Mpa, and \(\sigma_1, \sigma_2\) and \(\sigma_3\) denote the hoop stress, axial stress and radial stress, respectively. It can be calculated that the von Mises stress of the outer wall of the cylindrical pressure vessel is 553 Mpa, while the von Mises stress of the inner wall is 733 Mpa. The stress on the inner wall of the casing exceeds the yield strength of this material. Based on the von Mises yield criterion [9], the casing is in a failed state. Although a uniform internal pressure cannot be used to exactly represent the frost heave force, the basic principles of the two forces acting on the sealed container are similar. Therefore, it can be approximated that due to the frost heave force, the comprehensive stress on the inner wall exceeds the yield strength of the material when the
comprehensive stress on the outer wall reaches 550 Mpa, which leads to the deformation failure of the casing.

4. Conclusions
This paper presents experimental results of the failure mechanism of tubing and casing under frost heave force. On the basis of the experimental results, the following meaningful conclusions are drawn:

(a) The water that fills the annulus of the tubing and casing is completely frozen and will produce a considerable frost heave force. Before the failure of the casing and tubing, the frost heave force is approximately equivalent to the internal pressure of 104 MPa in a thin-walled cylinder pressure vessel of the same size.

(b) Under the effect of frost heave force, the tubing is squeezed into an ellipse, and the casing undergoes irreversible plastic deformation at the location of stress concentration.

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