Study on the stability of tubing under pressure operation

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Abstract: The operation with pressure is to carry out the lifting and lowering of the tubing or oil rod without releasing the pressure. Compared with traditional downhole operation, the operation with pressure can ensure the upward and downward of the string without pressure relief. The effective plugging of the inside of the oil pipe and the annulus of the oil jacket is the main characteristic of the operation under pressure. When the tubing is lifted, the interior of the tubing is sealed and blocked due to the downhole pressure, it will generate upward force on the tubing, which will make it difficult to run the tubing. The project uses a down-pressure device to assist the down-flow of the tubing. If the down-pressure is too large, buckling instability occurs, which increases the construction difficulty for the down-run operation. Combining elasto-plastic mechanics buckling instability theory and finite element simulation method to study the compression stability of tubing under pressure. The variation law of critical buckling force of tubing diameter, length and wall thickness under pressure is analyzed by numerical model, which provides the basis for equipment design and process plan formulation.

1.Introduction
Pressure operation mainly refers to the oil and gas well head under pressure, using professional equipment in the wellbore operation. One of the most applicable technologies in the field of oil and gas exploration and development, the application rate of this technology in foreign oil and gas Wells exceeds 90%, and the number of Wells constructed every year is more than 5000 [1-3]. In the 1980s, vehicle-mounted working machines appeared with pressure working devices, and this technology has been rapidly promoted in the whole foreign market [4]. At present, it has been widely used in underbalance drilling, side drilling, workover, completion, perforation, oil testing, testing, fracturing acidification and emergency operations abroad [5-8].

Blockage in the oil pipe when oil and water wells are under pressure is a basic requirement of the operation. The plug is delivered to the inside of the tubing, and the inside of the tubing is effectively sealed by the expansion of the barrel and the self-sealing of the barrel[9,10]. When the tubing is lifted and lowered, due to the existence of the downhole pressure, the jacking force is generated on the tubing, which will cause the tubing to face the difficulty of running down. The downforce auxiliary device with pressure is used to overcome the jacking force on the string to complete the downflow
operation [11]. Downhole pipe string is mostly long and thin, which is prone to buckling and instability under pressure, and increases the construction difficulty for downhole operation. When the down pressure exceeds the yield strength of the pipe string, the pipe string will elastically bend and even plastically deform, causing irreversible damage to the pipe string [12]. The research on the instability of the run-in string will help prevent and reduce the phenomenon of plastic bending, improve the success rate of the tubing under pressure, and promote large-scale oil and gas field exploitation.

Combining the buckling instability theory of slender members under pressure and finite element simulation methods are used to study the pressure stability of tubing under pressure. Through the numerical model simulation analysis, provides the basis for the equipment design and the process plan formulation.

2. The theoretical analysis

2.1 Buckling analysis theory of slender tubes

Suppose the pressure coincides with the axis of the member. When the pressure increases gradually but is less than a certain limit value, the member keeps the linear balance. Using a small lateral interference force to slightly bend it (Fig 1a), the linear shape can still be restored after the interference force is removed (Fig 1b). This indicates that the balance of the straight shape of the bar is stable. As the pressure gradually increases to a certain limit, the linear equilibrium becomes unstable and becomes the equilibrium of the curve shape. If the lateral interference force is used to make it bend slightly, after the interference force is removed, it will maintain the curve shape balance and cannot restore the original linear shape (figure 1c). The limit value of the above pressure is called the critical pressure or critical force, denoted as \( F_{cr} \). The linear equilibrium transition of the pressure bar is curved equilibrium, which is called instability and also called buckling.

\[
F_{cr} = \frac{\pi^2 EI}{(\mu l)^2}
\]

Where: \( F_{cr} \) - Elastic modulus of material, GPa; \( I \) - Cross-sectional moment of inertia, m⁴; \( \mu \) - Pressure rod length factor; \( l \) - Length, m; The constraint conditions are different under pressure, and the length factor \( \mu \) takes different values, as shown in Table 1.

| Constraint                          | \( \mu \) |
|-------------------------------------|-----------|
| With both ends hinged               | 1         |

![Fig 1. Force analysis](image-url)
One end is fixed and the other is free & 2 \\
Both ends fixed & 0.5 \\
One end is fixed and the other end is hinged & 0.7 \\

2.2 Forced buckling analysis
Use an operating device with pressure to lift a tubing with an internal plug down to the fully enclosed ram of the double ram preventer. In the first few pipelines, there is no tubing in the well, which has the maximum upper jacking force, and the tubing is held tight by the ring bop, with the maximum resistance. Equipment such as oil cylinders must be used to control tubing pressure into the well. Fig. 2 shows the device of type BYJ-A 65-35DQ with pressure operation.

![Fig 2. Part of device with pressure operation](image)

As the weight of the tubing that enters the downhole is greater than the upper jacking force of the well pressure on the tubing, the oil cylinder can no longer be used. Therefore, the tubing can be regarded as a pressure rod with one end fixed and the other end free under the action of the oil cylinder. In the early stage of the lower pipe, when the axial force on the pipe exceeds $F_{cr}$ certain critical buckling load, buckling deformation will occur in the pipe string.

3. Finite element simulation model

3.1 Model building
In order to research the buckling of the tubing under pressure, API J55 steel tubing is used for analysis. The characteristics of the tubing material parameters are taken according to the APII 5CT standard [13], as shown in Table 2 below.

| Table 2. API J55 tubing material parameters |
|---------------------------------------------|
| Elastic modulus /MPa | Poisson's ratio | Yield strength /MPa | Tensile strength /MPa |
| $2.1 \times 10^5$ | 0.3 | 379 | 519 |

The model size parameters adopt API standard specifications, and the finite element model adopts solid186 solid element modeling. To improve the calculation accuracy, the model mesh is divided by a hexahedral mapping mesh, as shown in Figure 3a. The model boundary condition is that given the size of the tubing, a fixed constraint is applied to one end of the tubing model and a load is applied to the other end, Figure 3b. The load gradually increased and finally reached the critical force of tubing buckling.
3.2 Model validation

In order to verify the reliability of the model, an API tubing with a size of 60.33mm × 4.83mm × 2000mm was selected for model verification. The drilling engineering technical manual [14] found that the API casing J55 60.33mm × 4.83mm (Fig 3a) has an internal pressure strength of 53.1 MPa, an anti-extrusion strength of 55.8 MPa, a connection strength of 251.38 kN, and a yield strength is 379 MPa. An internal pressure of 53.1 MPa, an external pressure of 55.8 MPa, and an axial tensile force of 251.38 kN were respectively applied to the model. The corresponding stress results are shown in Fig 4.

Figure 4 shows that when the model is subjected to an internal pressure of 53.1 MPa, an external compression force of 55.8 MPa, and an axial tensile force of 251.38 kN, the corresponding maximum stresses are 372 MPa, 376 MPa, and 369 MPa. The deviation relative to the yield limit of 379 MPa were 1.85%, 0.80%, and 2.64%, respectively. This illustrates the reliability of the model.

Based on the expression (1) and the data in Table 1, the comparative analysis of the critical force of 60.33mm × 4.83mm × 2000mm and the numerical simulation results of the model are shown in Table 3 below.

| Results of this article /KN | Numerical analysis /KN | deviation |
|---------------------------|------------------------|-----------|
| 41.721                    | 42.321                 | 1.4%      |

The analysis of the model and results above confirms the feasibility of the model, and subsequent research will be carried out on the basis of this model.
4. Tubing buckling simulation analysis

4.1 Tubing size
In the early stage of tubing run-in, there is no tubing in the well, and the jacking force is the largest. When it is pushed down, the resistance is also the largest. Increasing the downforce of the oil cylinder can easily cause the downturned tubing to fail. Therefore, buckling forces of different sizes of tubing are analyzed.

(a) 60.03mm×6.45mm  (b) 73.03mm×7.01mm  (c) 88.9mm×6.45mm  (d) 101.6mm×6.65mm

Fig 5. Buckling of tubing of different sizes

Fig 5 shows the buckling stress cloud diagrams for different API standard tubing sizes at the same length of 2m. In order to avoid the influence of wall thickness, the wall thickness of tubing is close. Fig. 6 shows the variation trend of buckling force in studying the change of tubing outside diameter size. Fig. 5 and Fig. 6 show that the buckling force of tubing increases with the increase of diameter, but the increasing trend of buckling force decreases gradually with the increase of tubing compression length. Fig 6b shows that when the length is in the 4-5m section, the buckling forces of different diameter oil pipes are close, indicating that the influence of the diameter of the oil pipe on the critical buckling force is within a certain length range. Therefore, under the condition of satisfying the diameter size, the large diameter tubing is preferred and the length of compression is minimized.

4.2 Tubing length
During the tubing running, as the running depth increases, the length of the tubing under pressure changes from top to bottom, and the flexing force of the tubing also changes. The following figure shows the variation of buckling force under loading of different lengths of tubing.
Fig. 7 c and d show the trend of critical buckling force change of tubing with external diameter of 73.03mm and 88.9mm at different lengths. Fig a and b are stress cloud diagrams for 88.9mm × 5.49mm under buckling at 2m and 3m. With the increase of compression length, the critical buckling force of tubing decreases gradually, and the variation trend of critical buckling force under different wall thickness is basically the same. The buckling force of length 1-3m is relatively large, but the critical buckling force decreases greatly with the length. The small buckling critical force in the 4-5m length is due to the longer the material, the smaller the rigidity, and the deformation is easy to occur under load. For certain compression length ranges, wall thickness can be considered to prevent buckling failure. On the contrary, the downforce can be adjusted appropriately to improve the downforce efficiency under the condition that the length of tubing under pressure is not buckling.

4.3 Tubing wall thickness

The working conditions of the downhole levels are complex and different. In order to reduce tubing damage, different wall thickness tubing will be selected at different levels to increase service life. Therefore, the pressure change of the tubing wall thickness must be considered when pressing the tubing.
Fig. 8 shows that with the increase of wall thickness, the buckling force of tubing increases almost linearly, and the change trend of critical buckling force is basically the same at different lengths and outside diameters. The critical force of buckling is larger in the tubing section with larger wall thickness and smaller length, and the rod is relatively stable. The tubing section with small wall thickness and large length has small critical buckling force and is prone to buckling. With 2m and 3m lengths, the wall thickness increases, and the range of buckling changes is large. Wall thicknesses with 4m and 5m lengths have less effect on buckling forces. However, the increase of wall thickness will increase the weight of the tubing and increase the downhole connection load. Therefore, the compression length and tubing diameter can be considered comprehensively when choosing the wall thickness of the tubing.

5. Conclusion
The finite element method was used to perform numerical simulation buckling analysis of the tubing under pressure, and the variation law of tubing size, length and wall thickness buckling force was obtained. The conclusion is as follows.

(1) The buckling force of tubing increased with the increase of diameter, but the increasing trend of buckling force decreased gradually with the increase of tubing compression length. Large diameter tubing is preferred when the diameter of tubing is satisfied. At the same time to minimize the length of compression.

Fig. 8c and d are the trends of the critical buckling force of oil pipes with outer diameters of 73.03mm and 88.9mm under different wall thicknesses. a and b are the buckling stress clouds with wall thickness of 5.51mm and 8.72mm, respectively.

(c) Outer diameter 73.03mm
(d) Outer diameter 88.9mm

Fig 8. Buckling forces of different wall thickness
(2) As the length increases, the critical pressure of tubing buckling gradually decreases. The longer the material, the more slender the performance, in the load prone to instability. Increasing wall thickness can be considered to prevent buckling failure in a certain compression length range.

(3) With the increase of wall thickness, the buckling force of tubing increases almost linearly. The wall thickness is large and the tubing is relatively stable, but it will increase the weight of the tubing and increase the connection load of the well. The selection of wall thickness takes into account the compression length and tubing diameter.

(4) The compressive capacity of different sizes of tubing in different lengths is calculated, which provides a basis for the formulation of construction process plan.

Acknowledgments
Study on the stability of tubing under pressure operation is supported by the Sichuan science and technology program (2019YFG0305, 2018GZ0429, 2018CC0098)

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