Research on Annular Frictional Pressure Loss of Hydraulic-Fracturing in Buckling Coiled Tubing

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Abstract. Compared with conventional hydraulic fracturing, coiled tubing (CT) annular delivery sand fracturing technology is a new method to enhance the recovery ratio of low permeability reservoir. Friction pressure loss through CT has been a concern in fracturing. The small diameter of CT limits the cross-sectional area open to flow, therefore, to meet large discharge capacity, annular delivery sand technology has been gradually developed in oilfield. Friction pressure is useful for determining the required pump horsepower and fracturing construction design programs. Coiled tubing can buckle when the axial compressive load acting on the tubing is greater than critical buckling load, then the geometry shape of annular will change. Annular friction pressure loss elevates dramatically with increasing of discharge capacity, especially eccentricity and CT buckling. Despite the frequency occurrence of CT buckling in oilfield operations, traditionally annular flow frictional pressure loss considered concentric and eccentric annuli, not discussing the effects of for discharge capacity and sand ratio varying degree of CT buckling. The measured data shows that the factors mentioned above cannot be ignored in the prediction of annular pressure loss. It is necessary to carry out analysis of annulus flow pressure drop loss in coiled tubing annular with the methods of theoretical analysis and numerical simulation. Coiled tubing buckling has great influence on pressure loss of fracturing fluid. Therefore, the correlations have been developed for turbulent flow of Newtonian fluids and Two-phase flow (sand-liquid), and that improve the friction pressure loss estimation in coiled tubing operations involving a considerable level of buckling. Quartz sand evidently increases pressure loss in buckling annular, rising as high as 40%-60% more than fresh water. Meanwhile, annulus flow wetted perimeter increases with decreasing helical buckling pitch of coiled tubing, therefore, the annulus flow frictional pressure loss rapidly increases with decreasing helical buckling pitch. The research achievement provides theoretical guidance for coiled tubing annular delivery sand fracturing operation and design.
1. Introduction
Hydraulic jet fracturing is set of new stimulation technology, it has a variety of functions, such as perforation, fracturing, isolation and so on, and it is suitable for low permeability reservoir in vertical well and horizontal well stimulation, and it is also a kind of effective method for fracturing stimulation. At present, the technology is used more and more widely in oilfield production process in our country. Coiled tubing fracturing technology integrates superiority of hydraulic jet fracturing perforating and flexibility of coiled tubing drag, which greatly improving the hydraulic jet fracturing operation efficiency. At the same time, the application of the technology has great importance to reducing the cost of oilfield development, enhancing oil recovery rate.

References [1-2] introduced the development of fracturing technology at home and abroad, an enormous amount of research effort goes into the flow rule of fracturing fluid by Haccislamoglu, Moises, Shah, Richard, Vibhas J et al, empirical formula of different fluids obtained by experimental method [3-6]. Domestic scholars Cui Haiqing, Wang Haige, Liu Yongjian et al have made a lot of research work in fluid pressure loss analysis of Newtonian fluid and non-Newtonian. These research results provide a theoretical basis for coiled tubing hydraulic jet fracturing technology [7-9].

The frictional pressure loss of fracturing fluid is an important research subject in the study of hydraulic fracturing technology. When the axial compressive load of coiled tubing is more than the critical buckling load, the coiled tubing will buckle in the wellbore. The buckling degree of coiled tubing can affect the hydraulic loss calculation of the coiled tubing and the wellbore. It is important to accurately predict the friction pressure loss of fracturing fluid in annular, which directly determines the required power, bottom hole pressure and maximum wellhead pressure.

In this paper, the influence of the coiled tubing fracturing string buckling and eccentricity on the frictional pressure loss of the annular fracturing fluid is studied.

2. Annulus Pressure Loss Analysis of Buckling Coiled Tubing
To provide the pushing force to the downhole tools in horizontal wells, axial compressive load of coiled tubing would exceed the critical buckling load. When the compressive load is below the critical buckling load, the coiled tubing can sustain the compressive load without buckling, and when it is above the critical buckling load, the string would be sinusoidal buckling. As the compressive load increases beyond the critical helical buckling load in the well, coiled tubing would be helical buckling. If the coiled tubing is buckling, the flow in the annulus combines pipe eccentricity with helical or sine buckling.

![Figure 1. Coiled tubing buckling state (no buckle, sine buckle, helical buckle)](image)

2.1. Basic Assumption
Fracturing fluid is incompressible fluid in annulus; flow rate of fracturing fluid is constant; the fluctuation effect of fracturing fluid is not considered.
2.2. Buckling Analysis of Coiled Tubing

Obviously, the estimation of the friction pressure loss anticipated in annulus during coiled tubing fracturing operations is extremely valuable. In hydraulic fracturing operations, a reliable assessment of the required pump horsepower depends on friction pressure loss estimates in the coiled tubing and annulus. In order to accurately calculate friction pressure in annulus, buckling deformation state of coiled tubing is need to study firstly. Buckling coiled tubing changes geometric shape of annulus, so it has a certain effect on the cyclic pressure loss of fracturing fluid in the annulus.

It is vital to study the buckling deformation state of coiled tubing to describe the actual working state of the underground. At the same time, the buckling state of coiled tubing has a certain effect on the pressure loss of fracturing fluid in the annulus. Buckling determinant criteria of coiled tubing fracturing string is determined by the formula (1) [10].

\[
\begin{align*}
F &> -2 \sqrt{\frac{Elq \sin \alpha}{r}} \quad \text{no buckle} \\
-2 \sqrt{\frac{2Elq \sin \alpha}{r}} &< F < -2 \sqrt{\frac{Elq \sin \alpha}{r}} \quad \text{sine buckle} \\
F &\leq -2 \sqrt{\frac{2Elq \sin \alpha}{r}} \quad \text{helical buckle}
\end{align*}
\]

Where, \( F \) is axial force of fracturing string, N; \( EI \) is flexural rigidity, \( \text{N} \cdot \text{m}^2 \); \( q \) is buoyancy weight of unit coiled tubing, N/m; \( r \) is radius difference between wellbore and pipe string, m; \( \alpha \) is average well deviation, rad.

To further study the effect of buckling string on the pressure loss of annular flow, firstly, the pitch of coiled tubing is determined; the relationship between the pitch and the axial force of the coiled tubing is determined by the formula (2). The difference between the length of the coiled tubing and the depth of well is determined by the formula (3).

\[
P_{\text{buckle}} = 2\pi \sqrt{\frac{2EI}{F}}
\]

\[
\Delta l = L \left[ \left( \frac{2\pi r}{P_{\text{buckle}}} \right)^2 + 1 \right]^{-1}
\]

Where, \( P_{\text{buckle}} \) is pitch of coiled tubing helical buckling, m; \( \Delta l \) is length change caused by coiled tubing buckling, m; \( L \) is the depth of well, m.

2.3. Annulus pressure loss analysis of buckling coiled tubing

Coiled tubing fracturing string buckling will change the fluid flow region in annulus. At the same time, it also has certain influence on fluid circulation pressure loss in annular between coiled tubing and casing. However, due to the coiled tubing annulus fluid has characteristics of turbulence, multiphase flow, so the internal flow is very complex, and traditional calculation method is difficult to describe flow rule of fluid. Therefore, it is necessary to use fluid analysis software to analyse annulus pressure drop of buckling coiled tubing, fluid dynamics analysis software is used in this research.

3. Numerical Simulation Analyses

In the process of fracturing operation, the coiled tubing may be in buckling condition due to the well bending and axial load. In uniformly eccentric annuli, higher velocities are predicted in the wider part of a cross-section. Due to variations of eccentricity along the wellbore, fluid will decelerate at the wide
part, and it will accelerate at the narrow part. Firstly, geometric model of the buckling coiled tubing needs to be established, and model parameters are shown in table 1. The simulation analysis is carried out in the 5-1/2in casing, a contrastive analysis of the annular flow pressure loss under different length of coiled tubing and different pitch conditions, analysis results as shown in figure 3-4.

**Table 1. Parameters of geometric model.**

| Outer diameter $D_0$ (mm) | Wall thickness $(mm)$ | Length $L_0$ (m) | Outer diameter $d_0$ (mm) | Wall thickness $(mm)$ | Length $L_s$ (m) | Coiled tubing buckling pitch $P_{buckle}$ (m) | Length variation caused by buckling $\Delta l$ (mm) |
|--------------------------|----------------------|------------------|--------------------------|----------------------|------------------|-------------------------------------------|---------------------------------------------|
| 139.7 (5-1/2in)          | 7.72                 | 1.0              | 60.325 (2-3/8in)         | 4.445                | 1.005            | 1.02                                       | 2                                           |
|                          |                      |                  |                          |                      |                  |                                           | 5                                           |

**Figure 2.** Geometric model of coiled tubing buckling.

**Figure 3.** Fluid pressure loss for vary annular injection rate (fresh water- turbulent).
Figure 4. Fluid pressure loss for vary annular injection rate (two-phase turbulent, sand content 10%).

4. Conclusion
(1) The correlations have been developed for turbulent flow of Newtonian fluids and laminar flow of Power-law guar fluids, and that improve the friction pressure loss estimation in coiled tubing operations involving a considerable level of buckling.

(2) Under the same simulation conditions, annulus flow wetted perimeter increases with decreasing helical buckling pitch of coiled tubing, therefore, the annulus flow frictional pressure loss increases with decreasing helical buckling pitch.

(3) Quartz sand evidently increases pressure loss in buckling annular, rising as high as 40%-60% more than fresh water.

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