Numerical simulation of foam flow pressure drop in coiled tubing spiral section

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Abstract. A user-defined function and a numerical simulation method were used to analyze the pressure drop of foam flow in the coiled tubing spiral section, and the calculated pressure drop was compared with the simulated pressure drop. For foam flow in the straight section, as the influences of acceleration pressure drop and actual velocity profile were considered, the simulated pressure drop is higher than the calculated pressure drop. For foam flow in the spiral section, due to the compressibility, the foam physical properties change with pressure. Therefore, at different outlet pressures, the velocity profile and density profile are different at the same spot. Centrifugal force makes the velocity profile unsymmetrical. Outlet pressure, gas injection rate, and curvature have significant influence on pressure drop. During the hydraulics design for coiled tubing drilling with foam, the foam injection pressure should be as high as possible to decrease the pressure drop of foam flow in the spiral section.

1. Introduction
Foam is a drilling fluid commonly used in underbalanced drilling (UBD) comprising of water, gas (air or nitrogen) and foaming agent, and can be used to drill through zones with excessive water content or bad leakage or sensitive zones. Since the 1960's[1], foam has been in UBD and delivered good performance[2]-[5]. Coiled tubing drilling without need to make connections has better safety and higher efficiency, and makes underbalanced drilling easier[6]. Coiled tubing drilling with foam has the advantages of both. In such drilling, the calculation of pressure drops in the spiral section, straight section, and annulus is critical to the design of drilling fluid/ gas injection rate, injection pressure, and annulus backpressure. There were a large number of studies about the flow rule and pressure drop of foam in the straight section and annulus by experiments and numerical simulation at home and abroad[7]-[9]. In references[7]-[9], the assumed foam density and rheological parameters were fixed values in a simulation, which, however, are variables in fact. There were few studies on foam flow in the spiral section: Khade S D et al studied the pressure drop of polymer foam flow in the spiral section and fitted a formula which, however, was not applicable to calculating the pressure drop of water-based foam flow in the spiral section. In addition, it has been found in a large number of experiments and numerical simulations that Newtonian fluids and non-Newtonian fluids have secondary vortex due to centrifugal forces and therefore cause big pressure drop when flowing in the coiled tubing spiral section[11]-[13]. For this reason, it is very necessary to study the pressure drop of foam flow in coiled tubing spiral sections. In this study, we performed a numerical simulation to study the influence of...
different outlet pressures, injection gas-liquid ratios, and curvatures on the foam flow in coiled tubing spiral sections.

2. Physical properties of foam

There have been a lot of studies on the physical properties, especially stability and rheological property of foam, carried out at home and abroad. These studies show that foam is a typical non-Newtonian fluid and its rheological property is described using the power law model or Bingham model. We used the power law model and determined the consistency coefficient and rheological index using equations (1) and (2) as follows [14]:

\begin{equation}
K = 0.3543e^{3.5163\Gamma} \\
n = 1.2085e^{-1.9897\Gamma} \quad \Gamma \leq 0.915
\end{equation}

\begin{equation}
K = -102.8182\Gamma + 103.2730 \\
n = 2.5742\Gamma - 2.1649 \quad 0.915 < \Gamma < 0.98
\end{equation}

where, \(K\) —— consistency coefficient, \(n\) —— rheological index, \(\Gamma\) —— foam mass.

If the foam mass \((\Gamma_1)\) in state 1 \((p_1, T_1)\) is given, the foam mass \((\Gamma_2)\) in state 2 \((p_2, T_2)\) can be expressed as follows [1]:

\begin{equation}
\Gamma_2 = \frac{1}{1 + \frac{p_2 T_1}{p_1 T_2} \left( \frac{1}{\Gamma_1} + 1 \right)}
\end{equation}

The foam mass is calculated using the following equation:

\begin{equation}
\rho_f = \Gamma \rho_g + (1 - \Gamma) \rho_l
\end{equation}

Where, \(\rho_f\) —— foam density, \(\rho_g\) —— density of foam in gas phase, \(\rho_l\) —— density of foam in liquid phase.

3. Friction pressure drop model of foam flow in straight section

The friction pressure drop of foam flow in straight section is calculated using the Fanning equation as follows:

\begin{equation}
\Delta p = \frac{2\Delta L \overline{\rho_f} f_f \bar{u}_f^2}{d}
\end{equation}

where, \(\Delta p\) —— pressure drop of foam flow in a straight section, \(\Delta L\) —— length of straight section, \(\overline{\rho_f}\) —— average foam density, \(f_f\) —— Fanning friction coefficient, \(\bar{u}_f\) —— average velocity of foam flow in straight sections, \(d\) —— I.D. of the straight section.

If laminar flow occurs inside the straight section, \(f_f\) can be obtained using the following equation [14]:
where, Re —— Reynolds number.

If turbulent flow occurs inside the straight section, \( f_t \) can be obtained using the following equation [14]:

\[
\sqrt{\frac{1}{f_t}} = \frac{4.0}{n^{0.75}} \log \left( \text{Re} \cdot f_t^{1.02} \right) - \frac{0.395}{n^{1.2}}
\]

When foam flows inside the straight section, the foam density, foam mass, and velocity are all related to pressure, so \( \rho_f \), \( f_t \), and \( u_t \) in equation (5) change with pressure. Pressure drop must be obtained through iterations[15].

4. Establishment of physical model

4.1. Geometric model

According to the method in reference[11], a geometric model was built and grids were divided. Different roller diameters were used to analyze the influence of curvature on foam flow in spiral section of coiled tubing. In addition, a geometric model of straight section was established to compare the simulated pressure drop with calculated pressure drop, thus to verify the correctness of the user-defined functions.

| Section     | No. | O.D./mm | I.D./mm | Roller diameter/mm | Pitch/mm | Length/m | Curvature, \( d/D \) |
|-------------|-----|---------|---------|--------------------|----------|----------|---------------------|
| Spiral      | 1   | 73.0    | 65.1    | 2134               | 73.0     | 15       | 0.0342              |
| section     | 2   | 73.0    | 65.1    | 2489               | 73.0     | 15       | 0.0293              |
|             | 3   | 73.0    | 65.1    | 3302               | 73.0     | 15       | 0.0221              |
|             | 4   | 73.0    | 65.1    | 5080               | 73.0     | 15       | 0.0144              |
| Straight    | 5   | 73.0    | 65.1    | -                  | -        | 15       | 0                   |
| section     |     |         |         |                    |          |          |                     |

4.2. Mathematical model

Foam is compressible, so its density and mass change with pressure and temperature. If the mass flow rate and injected gas-liquid ratio of the foam injected in coiled tubing are given, the foam density, rheological parameters, and velocity at the inlet can be calculated according to the inlet pressure and equations (1) to (4), so the mass flow rate at the inlet can be used as an appropriate inlet boundary condition. At the inlet, only axial velocity exists and radial velocity and tangential velocity are 0 m/s. The outlet pressure is used as an outlet boundary condition to simulate the pressure drop of foam flow in the spiral section. Assuming that foam and coiled tubing wall surface have no mass sliding velocity, wall surface boundary conditions free of sliding velocity are used.

The pressure of foam varies at different nodes, so the mass, density, and rheological parameters of foam also vary at different nodes. Therefore, a user-defined function must be used to define the attributes of foam in FLUENT. According to equations (1) to (4), the user-defined function of foam density and rheological parameters were compiled in FLUENT.
5. Result analysis

5.1. Pressure drop of foam flow in straight section
This paper used user-defined functions to define foam density and rheological parameters. To verify the correctness of the mathematical model and user-defined functions, the simulated pressure drop of foam flow in straight section and the pressure drop calculated using equation (5) were compared. Table 1 shows the dimensions of straight section 5. The liquid injection rate was 0.078 m$^3$/min. The gas injection rates in normal state were 16, 18, and 20 m$^3$/min, and outlet pressures were 1, 2, 3, 4, and 5 MPa. Figure 1 shows the comparison results.

According to Figure 1, the calculated pressure drop is lower than the simulated pressure drop, because when calculating with empirical formulas, the average velocity and average density in the coiled tubing are used, while actual velocity and density in the straight sections are not fixed values on any section. In addition, foam is compressible and may cause acceleration pressure drop when it flows. Acceleration pressure drop is also a factor that causes the simulated pressure drop to be lower than the calculated pressure drop. The mathematical model and user-defined function were used to simulate the pressure drop of foam flow in spiral section next.

![Figure 1. Comparison between the numerical simulation result and calculation result using empirical formulas](image1.png)

5.2. Flow rule of foam in spiral section
Figure 2, Figure 3, and Figure 4 show the velocity profile, pressure profile, and density profile of spiral section 3 at the 1/4 length to the outlet and the liquid injection rate of 0.078 m$^3$/min, a gas injection rate in standard conditions of 16 m$^3$/min and outlet pressures of 1, 3, and 5 MPa. In each figure, 0 in the horizontal coordinate indicates the center of the cross section and values on the horizontal coordinates on closer side of the roller are negative while those on the further side of the roller are positive. The absolute value of the maximum and minimum horizontal coordinates is the radius of the coiled tubing.

![Figure 2. Velocity distribution at different outlet pressures](image2.png)
From Figure 1, the velocity distribution varies with outlet pressure. The higher the outlet pressure, the lower the velocity. Due to the impact of centrifugal force, the maximum velocity occurs on the furthest side of the roller.

According to Figure 3, the pressure distribution varies with outlet pressure. The higher the outlet pressure, the higher the pressure. The maximum horizontal coordinate corresponds to the highest pressure, which means that the highest pressure occurs on the tubing wall on the furthest side of the roller.

![Pressure distribution at different outlet pressure](image)

**Figure 3.** Pressure distribution at different outlet pressure

According to Figure 4, the foam density distribution varies with outlet pressure. The higher the outlet pressure, the larger the foam density. The largest foam density occurs on the tubing wall on the furthest side of the roller. Foam density can be calculated from pressure, so the pressure profile has the same change rule as the density profile.

6. **Factors affecting pressure drop of foam flow in spiral section**

The pressure drop of foam in spiral section is the biggest concern of an engineering design, so the following analysis focuses on the influence of outlet pressure, injected gas-liquid ratio, and curvature on pressure drop.

![Foam density distribution at different outlet pressures](image)

**Figure 4.** Foam density distribution at different outlet pressures
6.1. Outlet pressure
Spiral section 3 was simulated to analyze the influence of outlet pressure on pressure drop at the outlet pressures of 1, 2, 3, 4, and 5 MPa, liquid injection rate of 0.078 m$^3$/min, gas injection rates of 16, 18, and 20 m$^3$/min in normal state.

![Influence of outlet pressure on pressure drop](image)

Figure 5. Influence of outlet pressure on pressure drop

According to Figure 5, at the same gas injection rate, the higher the outlet pressure, the lower the pressure drop. As the mass flow rate of foam is constant, a higher outlet pressure would result in a higher pressure in the bending section of coiled tubing, more compressible gas in the foam, a lower gas volumetric flow rate, and therefore lower foam mass and velocity. A lower foam mass delivers higher density, lower viscosity, and lower friction pressure drop. Therefore, with other conditions unchanged, the higher the outlet pressure, the lower the pressure drop of foam flow in the spiral section. In other words, during the injection of foam through coiled tubing, the injection pressure should be as high as possible to decrease the pressure loss of foam flow in the spiral section.

6.2. Gas injection rate
Spiral section 3 was simulated to analyze the influence of injected gas-liquid ratio on pressure drop at liquid injection rate of 78 L/min, gas injection rates of 10, 12, 14, 16, 18, and 20 m$^3$/min in normal state, and outlet pressures of 1, 3, and 5 MPa.

According to Figure 6, the gas injection rate has significant impact on pressure drop. At given outlet pressure, the higher the gas injection rate, the higher the pressure drop. When the gas injection rate increases, the foam mass and velocity also increase while the foam density decreases. When the foam mass increases, the foam viscosity and velocity also increase, resulting in the increase of friction pressure drop. Therefore, with other conditions unchanged, the higher the gas injection rate, the higher the pressure drop of foam flow in the spiral section.
6.3. Curvature

Spiral sections 1, 2, 3, and 4 and straight section 5 were simulated to analyze the influence of curvature on pressure drop at liquid injection rate of 0.078 m$^3$/min, gas injection rates of 16 m$^3$/min in normal state, and outlet pressures of 1, 2, 3, 4, and 5 MPa.

According to Figure 7, the pressure drop increases with the curvature. In the spiral section, curvature has obvious influence on pressure drop.

![Figure 7. Influence of curvature on pressure drop](image)

According to the preceding analysis, outlet pressure has significant influence on pressure drop. During coiled tubing drilling with foam, pressure is different at different spots in a long spiral section, so the pressure drop of foam flow in spiral sections with the same length are different, but the pressure drop gradient of incompressible fluids in spiral sections is certain. The method for calculating the pressure drop of incompressible fluids cannot be used to compute the pressure drop of foam flow in a spiral section, and there is no existing empirical formula for calculating the pressure drop of foam flow in spiral section. Therefore, numerical simulation with FLUENT is an effective method.

7. Conclusion

(1) Centrifugal force makes velocity profiles unsymmetrical and foam compressibility makes velocity profiles and density profiles different at different spots.

(2) Outlet pressure, gas injection rate, and curvature have significant influence on pressure drop.
(3) During the hydraulics design for coiled tubing drilling with foam, the foam injection pressure should be as high as possible to minimize the pressure drop of foam flow in spiral sections.

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