Hydraulics analysis of the U-tubing effect in a riserless drilling system

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Abstract. As a newly developed marine drilling technology, riserless drilling (RD) shows obvious advantages for use in deep-water and ultra-deepwater petroleum resources exploitation. However, the available published hydraulic analysis models for RD are rare or imperfect, especially regarding the lack of accounting for the out-of-hole time. To analyse the actual flow characteristics of drilling mud in an RD system after the surface mud pumping is complete, this paper presents a new hydraulic simulation model of the U-tubing effect. The specific calculation methods of pressure loss in the drilling string and the wellbore annulus at different flow regimes (turbulent flow, transition flow, and laminar flow) are provided based on the Herschel-Bulkley (HB) rheological model. A case study shows that a critical volumetric flow rate (CVFR) exists for a specific RD system to just cause the standpipe pressure to become zero. Only when the initial pump circulation rate is greater than the CVFR can it ensure the normal operation of the RD. Otherwise, the fluid mud level inside the drilling string will drop, resulting in the u-tubing effect. In the first few seconds after the surface pump is shut down, the wellbore transient flow rate is influenced strongly by the initial circulation rate. When the initial flow rate is less than the CVFR, the transient flow rate is accelerated during the first few seconds, which is not the expected behaviour. The influence of the drilling string size, fluid density and rheological parameters of the drilling fluid on the transient flow rate and the Bottom Hole Pressure (BHP) are also considered. The results proved that the smaller values of the rheological parameters are beneficial for reducing the fluctuation of the BHP during the U-tubing process.

1. Introduction

Petroleum reserves on land will decline because of the continuous exploration and production of natural gas and oil resources. With the new theories, new technologies and new operations of drilling developed in recent years[1], the huge marine petroleum resources have gradually become the new sources of growth of energy development. Traditional offshore drilling is conducted using a larger diameter riser, which limits offshore drilling from extending to deep-water and ultra-deepwater areas. The reason for this limitation is described by Choe [2-3] (1998, 1999), Stair (2002), Schubert (2003), Carter (2005) and Mirrajabi (2010).

As an attractive dual-gradient offshore drilling technology, RD is beneficial for reducing the drilling cost, shortening the well construction period and lowering the selection standards of the drilling rig. The RD concept was first developed by Watkins (1969) to reduce rotating blowout preventer (BOP) wear and balance the subsea internal and external well pressures. In an RD system, the return mud is forced by the subsea pump to the surface through a smaller diameter pipe instead of
a larger diameter marine riser. According to published articles (Lima, 1998; Choe, 1998; Schubert, 2003) [4-5], the main function of the subsea pump is to maintain the wellhead pressure in the annulus to be equal to the hydrostatic pressure of seawater at the seafloor.

When making connections, taking tripping operations, or performing other no-drilling operations, the surface pump will stop working in an RD system. Because of the pressure imbalance inside the drilling string and the well annulus, the U-tubing effect occurs. A dynamic equilibrium governing equation is used by Choe (1998, 1999) and Jonggeun (2004) to analyse the transient flow rate and the corresponding mud level inside the drilling string during this process. However, the Power-Law model (without yield stress) is used in the hydraulic calculation. In addition, the specific calculation methods for the pressure loss in the drilling string and the wellbore annulus as well as for the bit pressure loss are not provided.

Based on the analysis, this paper presents a new hydraulic model for analysis of the U-tubing effect in an RD system based on the Herschel-Bulkley (HB) model (Platzer, 1996). The specific calculation methods of pressure loss are also provided; moreover, the parameters affecting the U-tubing process are also investigated. This research provides a guide for engineers to control the circulation rate to within a reasonable range of values before shutting down the surface pump. This study also provides some advice on how to weaken the fluctuation of BHP in an RD system when the U-tubing effect occurs.

2. Model

As mentioned above, the hydraulics of an RD is quite different from that of a conventional riser drilling system. To balance the internal and external well pressures, the subsea pump must continue to operate during the whole well construction process, regardless of whether drilling or no drilling operations are underway.

2.1. Drilling fluid rheological property

| Drilling fluid properties. | Table 1. | Measured data of FANN 35 viscometer. |
|---------------------------|---------|------------------------------------|
| Drilling mud density, g/cm³ | 1.3837  | S/W ratio                          |
| Temperature, °C            | 65.6    | Corrected solids, %               |
| Solid volume percentage, % | 21      | Low-gravity solid, %              |
| Synthetic volume percentage, % | 57      | High-gravity solid, %             |
| Water volume percentage, % | 22      | Chlorides, mg/L                   |

| Table 2. | Regression results of the rheological parameters. |
|----------|-----------------------------------------------|
| Rheological model | Rheological parameters | Average Error, Pa |
| BH model  | $\tau_0 = 6.27$ Pa, $\mu = 0.0416$ Pa.s | 2.32 |
| PL model  | $K = 1.7747$ Pa.s, $n = 0.4479$ | 1.72 |
| HB model  | $\tau_0 = 2.85$ Pa, $K = 0.3725$ Pa.s, $n = 0.6857$ | 0.29 |

The drilling fluid rheological property is closely related to the calculation of the hydraulic parameters. According to earlier scholars [6-9] (Horton, 2005; Erge, 2015), the Bingham plastic model (Hanks, 1967), Power-law model (Wallick, 1969), and HB model are the most frequently used models to describe drilling fluid rheological properties. This paper selects a synthetic-based drilling fluid from a Gulf of Mexico well (White, 1997). The properties of the drilling fluid and the measured data are listed in Table 1 and Table 2, respectively. Based on the measured data of a FANN 35 viscometer, the
rheological parameters of these three models are derived via regression analysis; the results are listed in Table 3 and plotted in Figure 1. As shown in Figure 1, the predictions of the HB model have the best agreement with measured values among the three models. Figure 2 shows a hydraulic illustration of a riserless drilling system. The average error in Table 3 also indicates that the HB model can precisely describe the thixotropy and shear thinning behaviour for this synthetic-based drilling fluid.

![Figure 1](image1.png)

**Figure 1.** Rheological curves of a synthetic-based drilling fluid for different models.

![Figure 2](image2.png)

**Figure 2.** Hydraulic illustration of a riserless drilling system.

### 2.2. Normal circulating state

The flow route of the drilling mud in an RD is shown in Figure 2. During normal well drilling, the pressure equilibrium relationship can be established as follows:

\[
p_{\text{spp}} = p_{\text{mp}} + \Delta p_{\text{r,p}} - \Delta p_b = p_{\text{bh}} \quad (1)
\]

\[
p_{\text{bh}} = p_{\text{s}} + \Delta p_{\text{r,a}} + p_{\text{ma}} \quad (2)
\]

\[
\Delta p_b = 0.81 \rho_m Q^2 / (C^2 d_{\text{w}}^4) \quad (3)
\]

where \( p_{\text{mp}} = \rho_m (h_{\text{w}} + h_{\text{bh}}) * 10^{-3} \), \( p_{\text{ma}} = \rho_m g h_{\text{bh}} * 10^{-3} \), and \( p_s = \rho_s g h_{\text{w}} * 10^{-3} \).

Combining Eq. (1) and Eq. (2), the pressure equilibrium of the RD during normal working conditions can be obtained:

\[
p_{\text{spp}} = \Delta p_{\text{r,p}} + \Delta p_{\text{s}} + \Delta p_{\text{r,a}} - \Delta p_{\text{m,w}} \quad (4)
\]

where \( \Delta p_{\text{m,w}} = (\rho_m - \rho_s) g h_w * 10^{-3} \).

Flow pressure losses \( \Delta p_{\text{r,p}} \) and \( \Delta p_{\text{r,a}} \) are two important hydraulic parameters for an RD; these losses change with drilling string size, circulation rate, and mud rheology. These two parameters in Eq. (4) are calculated by the methods presented as follow [10], respectively, in which three flow regimes (laminar flow, transition flow and turbulent flow) are considered.

Flow pressure loss in the drilling string. Shear stress at pipe wall \( \tau_{\text{wp}} \) and friction coefficient \( f \) are the two key parameters in calculating the flow pressure loss in the drilling string. The specific calculation equations are listed as follows:

\[
Q = \frac{\eta n R^4}{3 n + 1} \left( \frac{\tau_{\text{wp}}}{\tau_{\text{wp}}} \right) \left( 1 - \frac{\tau_{\text{wp}}}{\tau_{\text{wp}}} \right)^{-\frac{n}{2}} \left( 1 + \frac{2 n \tau_{\text{wp}}}{(n + 1) (2 n + 1)} \left( \frac{\tau_{\text{wp}}}{\tau_{\text{wp}}} \right)^{n+1} \right)^{-\frac{1}{2}}
\]

(5)

This is the general formula of the circulation rate and the shear stress at the pipe wall based on the HB model, which is suitable for different flow regimes. Eq. (5) comes from Fan (2014a) [11].

We apply the generalised Reynolds number from Fan (2014b) [12] in which an equivalent pipe diameter is used for the pipe flow:

\[
Re_{\text{wp}} = \frac{p_{\text{wp}} D_{\text{wp}} V_{\text{wp}}}{\mu_{\text{wp}}}
\]

(6)

where

\[
D_{\text{wp}} = \frac{8 V_{\text{wp}}}{\nu_{\text{wp}}}
\]

\[
\mu_{\text{wp}} = \frac{\tau_{\text{wp}}}{V_{\text{wp}}}
\]

(7)

Based on Eq. (6), the Reynolds number calculation equations of a Newtonian fluid and a Non-Newtonian fluid are unified in form.
To distinguish the different flow regimes, the criteria of the flow regimes from Khata\textit{ni}ar [13] (1994) and Schuh [14] (1964) are used:

\begin{align}
0 &< \text{Re}_p < \text{Re}_p^c; \quad \text{Laminar flow} \\
\text{Re}_p^c &\leq \text{Re}_p < \text{Re}_p^t; \quad \text{Transition flow} \\
\text{Re}_p^t &\geq \text{Re}_p; \quad \text{Turbulent flow}
\end{align}

where

\begin{align}
\text{Re}_p^c &\approx 3470 - 1370n' \\
\text{Re}_p^t &\approx 4270 - 1370n'
\end{align}

According to the criteria, the friction coefficient \( f \) at the different flow regimes is provided by Reed[15] (1993) and Dodge[16] (1959).

\begin{align}
f &= 16/\text{Re}_p; \quad \text{Laminar flow} \\
f &= f + (\text{Re}_p^t - \text{Re}_p)^{(f - f_1)/(\text{Re}_p^t - \text{Re}_p^c)}; \quad \text{Transition flow} \\
f &= 4n^{0.75} \text{lg} [\text{Re}_p^{1.4} \text{Re}_p^{-1} - 0.395n^{1.2}]; \quad \text{Turbulent flow}
\end{align}

The final flow pressure loss in the drilling string is:

\begin{align}
\Delta p_{fs}' &= 2f \frac{h}{D_p}\rho_n v'_a
\end{align}

Flow pressure loss in the annulus. The process of calculating the pressure loss in the annulus is similar with that in the drilling string. Based on the HB model, the general relation of the circulation rate \( Q \) and the shear stress in the annular wall \( \tau_{wp} \) is provided by Peng[17] (2013) as follows:

\begin{align}
Q &= \frac{nn'\rho}\pi(\text{Re}^{1/2})^{2n+1} \left( \frac{\tau_{wp}^+ - \tau_{wp}^-}{\tau_{wp}^+ + \tau_{wp}^-} - 1 \right)
\end{align}

Similarly, an annular equivalent diameter is introduced to define the generalised Reynolds number in the annulus:

\begin{align}
\text{Re}_{ga} &= \rho D_v \mu
\end{align}

The criteria of flow regimes in the annulus and the friction coefficient \( f_a \) are almost the same as that in the drilling string. The only differences are the computing formulas of \( \text{Re}_{ga} \) vs. \( \text{Re}_{ga} \) and \( n' \) vs. \( n_a \).

\begin{align}
\text{Re}_{ga} &= \frac{8v_a}{\nu_{wa}}; \quad \text{Drilling string} \\
\text{Re}_{ga} &= \frac{4v_a}{\nu_{wa} - 8v_a}; \quad \text{Annulus}
\end{align}

\begin{align}
f &= 16/\text{Re}_{ga}; \quad \text{Laminar flow} \\
f &= f + (\text{Re}_{ga}^t - \text{Re}_{ga})^{(f - f_1)/(\text{Re}_{ga}^t - \text{Re}_{ga}^c)}; \quad \text{Transition flow} \\
f &= 4n_a^{0.75} \text{lg} [\text{Re}_{ga}^{1.4} \text{Re}_{ga}^{-1} - 0.395n_a^{1.2}]; \quad \text{Turbulent flow}
\end{align}

The final pressure loss in the annulus is

\begin{align}
\Delta p_{fa}' &= 2f \frac{h_{wa}}{D_a}\rho_n v_a
\end{align}

As mentioned above, hydrostatic pressure inside the drilling string is higher than that of the annular wellhead at the sea floor. According to Eq. (4), when the circulation rate is very small, \( p_{app} \) has negative values. Meanwhile, \( \Delta p_{fs}, \Delta p_b, \) and \( \Delta p_{fa} \) are functions of the circulation rate; these three parameters increase with increasing volumetric flow rate. Thus, there must be a volumetric flow rate that just causes the value of \( p_{app} \) to be equal to zero; this volumetric flow rate is defined as the critical volumetric flow rate (CVFR). Only when the circulation flow rate exceeds the CVFR can the normal operation of the RD be ensured.

Table 4 lists the basic parameters of a deep-water well. The water depth is 3000 m, and the well depth is 9000 m. The CVFR is 30.25 L/s, based on the default data from Table 4. According to Eq. (4), the CVFR is influenced by the drilling string size, water depth and well depth, and mud rheology, among other factors. Figure 3 displays the CVFR vs. well depth for different water depths. Figure 4
shows a plot of the CVFR versus water depth for various well depth situations. The other basic parameters used are from Table 4. As expected, when the water depth remains unchanged, the deeper well depth requires the lower CVFR to maintain ordinary operation. When the well depth below the mud line is fixed, the deeper water depth requires the higher CVFR to maintain normal drilling operation.

Table 4. Basic parameters of a deep-water well.

| Parameter                                      | Value   |
|-----------------------------------------------|---------|
| Drilling mud density, g/cm$^3$                | 1.8569  |
| Seawater density, g/cm$^3$                    | 1.0303  |
| Acceleration of gravity, m/s$^2$              | 9.8     |
| Water depth, m                                | 3000    |
| Well depth, m                                 | 9000    |
| Hole diameter, m                              | 0.1937  |
| ID of casing, m                               | 0.2191  |
| Depth of casing point, m                      | 8700    |
| Length of drilling collar, m                  | 30      |
| OD and ID of drilling pipe, m                 | 0.127*0.1087 |
| OD and ID of drilling collar, m               | 0.2032*0.0826 |
| Number of bit nozzles                         | 3       |
| Diameter of bit nozzle, m                     | 0.02    |
| Yield stress (YS) of HB fluids, Pa            | 2.85    |
| Consistency coefficient, Pa.sn                | 0.3725  |
| Flow index                                    | 0.6857  |
| Circulation rate while drilling, m$^3$/s      | 0.0252  |
| Rate of penetration, m/hr                     | 3       |
| Seawater surface temperature, °C              | 21      |
| Wellbore temperature gradient above mud line, °C/100 m | -0.153 |
| Wellbore temperature gradient below mud line, °C/100 m | 1.35    |

2.3. U-tubing effect

As mentioned above, when the surface mud pump is shut down or the circulation flow is less than the CVFR, the mud level inside drilling string will drop because of gravity until a new equilibrium is reached; this phenomenon is the so-called U-tubing effect. During this process, the dynamic pressure equilibrium can be expressed as follows:

\[
\rho_y g h_x - \rho_y - \Delta p^*_{f,p} - \Delta p^*_{f,a} - \Delta p^*_{b} = \Delta p^*_{acc} \quad (20) \]

where \( h_x \) is the current fluid mud level above the mud line and \( \Delta p^*_{f,p} \), \( \Delta p^*_{f,a} \), and \( \Delta p^*_{b} \) are the current pressure loss in the drilling string, the pressure loss in the wellbore annular, and the bit pressure loss, respectively.

Because of the acceleration pressure loss \( \Delta p^*_{acc} \) in the wellbore, the true circulation rate is no longer equal to the pump displacement. Undoubtedly, these dynamic parameters vary with time. Note that the pressure losses \( \Delta p^*_{f,p} \) and \( \Delta p^*_{f,a} \) in Eq. (20) are also calculated by the methods presented as above. The only difference is that the mud level and the circulation rate are time-varying parameters during the U-tubing process.
2.4. Computational procedures for the U-tubing effect

Based on the model and the equations above, a MATLAB program is developed to analyse the transient circulation rate and mud level inside the drilling string for the U-tubing effect. The main steps of this calculation method are listed as follows:

1. Initialise $Q$ and $h_x$, ($h_e = h_a$);
2. Compute $\Delta p^*_{b}$, $\Delta p^*_{fp}$, and $\Delta p^*_{fa}$ using Eq. (3), respectively;
3. Calculate $\Delta p^*_{acc}$ based on Eq. (20);
4. Compute $a_{cp}$ and $a_{ca}$ by combining Eq. (21) and Eq. (22);
5. Calculate the average flow velocity increments $\Delta v_p$ and $\Delta v_a$ at a definite time interval $\Delta t$;
6. Compute the mud level drop height $\Delta h$ during $\Delta t$;
7. Calculate the new average flow velocities $v_{p1}$ and $v_{a1}$ and the new circulation rate $Q_1$;
8. Repeat steps 2—7 until the variation of the circulation rate is incredibly small.

The details of the relevant parameters in steps 5 to 7 are presented as follows.

Procedure parameters of the U-tubing process. During the U-tubing process, the mud level $h_x$, the mud average flow velocities $v_p$ and $v_a$, and the circulation rate $Q$ are all changing with time. At each time step $\Delta t$, the increment of the average flow velocity in the drilling string and the well annular are $\Delta v_p$ and $\Delta v_a$ as follows:

$$\Delta v_p = a_{cp} \times \Delta t$$ (23)

$$\Delta v_a = a_{ca} \times \Delta t$$ (24)

At the same time, the mud level drop height $\Delta h$ can be described by:

$$\Delta h = v_p \times \Delta t + 0.5 \times a_{cp} \times (\Delta t)^2$$ (25)

After the time interval $\Delta t$, the new average flow rates in the drilling string and the well annulus are $v_{p1}$ and $v_{a1}$, and the new circulation rate is $Q_1$.

$$v_{p1} = v_p + \Delta v_p$$ (26)

$$v_{a1} = v_a + \Delta v_a$$ (27)

$$Q_1 = 0.25 \pi D^2_{pi} v_{p1}$$ (28)

3. Case discussion

Define the time interval $\Delta t = 1$ s and the final calculation error of the circulation rate $\Delta Q = 10^{-5}$ m$^3$/s.

Based on the equations and calculation procedures mentioned above, the initial parameters shown in Table 4 are used to analyse the whole U-tubing process.

Figure 5 shows the transient average flow rate in the drilling string and the wellbore annulus considering the U-tubing effect. Both the average flow rate in the drilling string and the wellbore annulus rapidly increase during the initial 13-second period. The average flow rate increases from 2.7156 m/s to 3.2053 m/s in the drilling string and from 1.0066 m/s to 1.1882 m/s in the wellbore annulus. Subsequently, the average flow rate sharply decreases within the first 500 seconds. Finally, the average flow rate decreases slowly and decreases exponentially to zero.
Figure 6 describes the transient pressure loss versus time after the mud pump is shut down. The pressure loss in the drilling string, wellbore annulus and bit pressure loss are all increased within the initial 13 seconds due to the increase in the circulation rate. Drilling mud in both the drilling string and the wellbore annulus is in turbulent flow within the first 273 seconds. Fluid in the annulus turns into transition flow during the period from 273 to 382 seconds and then goes into laminar flow. Note that the flow regime change occurs earlier in the annulus than that in the drilling string. Within 1500 seconds, approximately 64.79% of the system pressure loss occurs in the drilling string, and the amounts of pressure losses in the annulus and the bit are 32.58% and 2.63%, respectively.

Figure 7 shows the transient flow rate versus time plots for different initial circulation rates (25.2 L/s, 30.5 L/s, and 35.3 L/s) after the surface mud pump is shut down. Within the initial 16 seconds, the variations of the transient flow rate of the three situations are not as expected. When the initial volumetric flow rate (25.2 L/s) is less than the CVFR (30.25 L/s), the pressure difference of the sea water section $\Delta p_{m,w}$ is sufficient to overcome the system pressure loss. At this moment, the positive acceleration pressure loss $\Delta p_{\text{acc}}$ accelerates the flow rate in the wellbore. Subsequently, the mud level in the drilling string decreases while the volumetric flow rate increases, resulting in a slow decrease in $\Delta p_{\text{acc}}$ to zero. When the initial volumetric flow rate (35.3 L/s) is greater than the CVFR (30.25 L/s), $\Delta p_{\text{acc}}$ has a negative value; such a situation could slow down the flow rate in the wellbore. For an initial volumetric flow rate (30.5 L/s) approximately equal to the CVFR (30.25 L/s), $\Delta p_{\text{acc}}$ is approximately zero; thus, the variation of flow rate is slight at this condition.

After the first 16 seconds, the volumetric flow rate and the mud level in the drilling string of the three cases become nearly the same: 29.67 L/s and 2953 m. Afterwards, drilling mud undergoes a free fall inside the drilling string and the variation of the flow rate of the three cases is always almost the same. During this period, the flow rate decreases sharply until the flow regime changes from turbulent to transition flow, and it decreases exponentially to zero when the flow regime transforms to laminar flow. The transient flow rate curves in Figure 7 indicate that different initial circulation rates have little influence on the total time for achieving a new equilibrium after the surface pump is shut down.

Similarly, the corresponding BHP curves during the U-tubing process are shown in Figure 8. The curves of the transient BHP are similar to the curves of the transient flow rate in Figure 7. The difference is that the smaller initial circulation rate corresponds to the higher BHP within the first 16 seconds. This difference occurs because when initial flow rate (25.2 L/s) is less than the CVFR (30.25 L/s), the flow rate in the wellbore is accelerated and $\Delta p_{\text{acc}}$ has positive values. However, when the initial flow rate (35.3 L/s) is greater than the CVFR, the flow rate in the wellbore decreases and $\Delta p_{\text{acc}}$ has negative values. In addition, the difference of bottom hole pressure of the three cases also decreases over time.
4. Parametric analysis of the U-tubing process

According to the analysis above, the main influence factors of the transient volumetric flow rate and the BHP during the U-tubing process are the drilling string size, the drilling fluid density, and the rheological parameters of drilling fluid [18-22].

4.1. Inference of the drilling string size on the U-tubing effect

We study on the transient volumetric flow rate vs. time for different drilling string sizes. For the same initial circulation rate and mud rheological property during the U-tubing process, the larger the drilling string size, the faster is the transient volumetric flow rate. The time points of the flow regime changes and the total time for a new equilibrium are almost the same for the three cases. In addition, the difference in transient flow rate during the first few seconds in Figure 9 is caused by the difference in the results compared to the initial circulation rate (31.5 L/s) with the CVFR of the three cases. The CVFR of 114.3 mm, 127 mm and 139 mm OD drilling strings are 23.5 L/s, 30.2 L/s and 35.4 L/s, respectively.

Figure 10 illustrates the BHP vs. time when the U-tubing effect occurs for different drilling string sizes. The larger drilling string size corresponds to the higher BHP, with the other parameters fixed. This phenomenon occurs because the transient volumetric flow rate in a larger size drilling string is higher than that in a smaller size drilling string, as shown in Figure 9. The results in Figure 10 indicate that the smaller drilling string size is beneficial for reduction of the fluctuation of the bottom hole pressure during the U-tubing effect, with the other conditions remaining unchanged.

4.2. Influence of the drilling fluid density on the U-tubing effect

Figure 11 illustrates the transient flow rate vs. time for different initial circulation rates. The results in Figure 12 indicate that the larger drilling fluid density corresponds to the higher BHP, with the other parameters fixed. This phenomenon occurs because the transient volumetric flow rate in a larger density drilling fluid is higher than that in a smaller density drilling fluid, as shown in Figure 11. The results in Figure 12 indicate that the smaller drilling fluid density is beneficial for reduction of the fluctuation of the bottom hole pressure during the U-tubing effect, with the other conditions remaining unchanged.

![Figure 9. Transient flow rate vs. time for different initial circulation rates.](image)

![Figure 10. Bottom hole pressure vs. time for different initial circulation rates.](image)

![Figure 11. Transient flow rate vs. time for different initial circulation rates.](image)

![Figure 12. Bottom hole pressure vs. time for different initial circulation rates.](image)
Figure 11 shows the change in the transient flow rate with time for different drilling fluid densities. When the drilling string size and the initial circulation rate are fixed, the transient volumetric flow rate of the heavier drilling fluid is higher than that of the lighter drilling fluid. In addition, the transformation points of the flow regimes (both turbulent to transition flow and transition to laminar flow) occur earlier in the lighter drilling fluid situation. However, the total time required to achieve a new equilibrium of the three cases differ little. The differences in the BHP of the three cases are obvious, as shown in Figure 12. When the variation amplitude of the drilling fluid density is 6.45%, the change rate of the BHP is from 4.95 % to 5.26 %. The results in Figure 12 indicate that the BHP is sensitive to the change in drilling fluid density when the U-tubing effect occurs.

4.3. Influence of the drilling fluid rheological parameters on the U-tubing effect

We study on the variation of transient volumetric flow rate vs. time for different rheological parameters (YS, K and n, respectively) after the surface pump is shut down. Although the transient volumetric flow rate decreases with time, the variation trends are not the same for different conditions. In addition, the transformation points of the flow regime changes occur earlier with the increase in the rheological parameters YS, K and n.

![Figure 13. Transient flow rate vs. time for different YS values of the drilling fluid(Initial circulation rate is 30.5 L/s).](image)

![Figure 14. Transient flow rate vs. time for different K values of the drilling fluid(Initial circulation rate is 28.5 L/s).](image)

![Figure 15. Bottom hole pressure vs. time for different YS values of the drilling fluid(Initial circulation rate is 30.5 L/s).](image)

![Figure 16. Bottom hole pressure vs. time for different K values of the drilling fluid(Initial circulation rate is 28.5 L/s).](image)

For higher YS values of the drilling fluid, the laminar flow appears earlier and the duration time of this flow regime is much longer, as shown in Figure 13. The transient volumetric flow rates of different YS values are almost the same after approximately 1000 seconds. For different K values, the laminar flow also occurs earlier with higher K values; however, the transient volumetric flow rates are more complicated during this flow regime, as shown in Figure 14. In a laminar flow situation, the flow rate of the higher K values is lower than that of lighter K values of the drilling fluid before 500
10 seconds. Subsequently, the situations are just the opposite. Moreover, the transient flow rates of different K values are almost the same after approximately 2000 seconds. For different values of the flow index n, the main differences are located in the transition flow. The flow regime change also occurs earlier in the higher flow index condition. In addition, the duration time of the transition flow is shorter for smaller n values of the drilling fluid. In addition, the transient flow rate of the situation of smaller n values is higher during the turbulent flow regime. However, when the flow regime turns into the laminar flow situation, the transient flow rate of larger n values is higher than that of smaller n values. The transient flow rates of different n values are nearly coincident after approximately 1500 seconds.

The corresponding BHP curves of Figures 13, 14, 15, 16, 17 and 18, respectively. In general, the greater the values of the rheological parameters YS, K and n, the greater is the BHP during the U-tubing process. When the increments of YS, K and n are 61.07%, 22.38% and 4.48%, respectively, the variations of BHP are from 0.491% to 1.07%, 0.065% to 0.568% and 0.029% to 0.325%, respectively. For an RD system, the fluctuation of the bottom hole pressure during the U-tubing process can be reduced by using drilling fluids with smaller rheological parameters (YS, K and n).

**Figure 17.** Transient flow rate vs. time for different n values of the drilling fluid(Initial circulation rate is 33 L/s).

**Figure 18.** Bottom hole pressure vs. time for different n values of the drilling fluid(Initial circulation rate is 33 L/s).

5. Conclusions
This paper established a new hydraulics model of the U-tubing process in an RD system. The pressure loss in the drilling string and the wellbore annulus are calculated under three flow regimes (turbulent flow, transient flow and laminar flow) based on the HB model. The critical volumetric flow rate is introduced as the key parameter to analyse the U-tubing effect. The influence of the initial circulation flow rate, drilling string size, fluid density and rheological parameters of the drilling fluid on the transient volumetric flow rate and the BHP are fully studied. The main conclusions are as follows:

1) Only when the initial flow rate is greater than the critical volumetric flow rate can the normal operation of the riserless drilling system be ensured. Otherwise, the U-tubing effect will appear.

2) Different initial flow rates have little influence on the total time required to achieve a new equilibrium, when the other parameters are fixed during the U-tubing process. However, the differences in the transient volumetric flow rate are very obvious in the first few seconds for different situations.

3) After the surface pump is shut down, when the initial circulation rate is less than the CVFR, the transient flow rate will increase in the first few seconds. While the initial circulation rate is greater than the CVFR, the transient flow rate will decrease in the first few seconds.

4) The influences of the drilling string size and the drilling fluid density on the transient flow rate are similar. The higher values of drilling string size / drilling fluid density situations correspond to higher transient flow rates.
(5) The influence of the rheological parameters (YS, K and n) on the transient flow rate focuses on the transformation points of the flow regime change and the duration times of all of the flow regimes. The smaller values of rheological parameters are beneficial for reducing the fluctuation of the bottom-hole pressure.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| \( p_{\text{app}} \) | Stand pipe pressure, MPa |
| \( p_{\text{mp}} \) | mud hydrostatic pressure in the drilling string, MPa |
| \( p_{\text{bh}} \) | Bottom hole pressure, MPa |
| \( p_s \) | annular pressure in the wellhead at the sea floor, MPa |
| \( p_{\text{ma}} \) | mud hydrostatic pressure in the annulus, MPa |
| \( \Delta p_{f,p} \) | flow pressure loss in the drilling string, MPa |
| \( \Delta p_{f,a} \) | flow pressure loss in the annulus, MPa |
| \( \Delta p_{\text{bh}} \) | bit pressure loss, MPa |
| \( \rho_m \) | drilling mud density, \( \text{g/cm}^3 \) |
| \( C \) | nozzle coefficient, dimensionless |
| \( d_{\text{ne}} \) | nozzle equivalent diameter, m |
| \( p_{\text{m,w}} \) | pressure difference at the sea water section, MPa |
| \( \Delta p_{\text{acc}} \) | acceleration pressure loss, MPa |
| \( h_{\text{bh}} \) | wellbore depth below the mud line, m |
| \( h_w \) | water depth, m |

| Symbol | Description |
|--------|-------------|
| \( a_{\text{ep}}, a_{\text{ca}} \) | transient accelerated velocity in the drilling string and annulus, m/s |
| \( S_p, S_a \) | effective cross section of the drilling string and annulus, \( \text{mm}^2 \) |
| \( \tau_0 \) | yield stress of the drilling fluid, Pa |
| \( K \) | Consistency coefficient, Pa.s\(^n\) |
| \( n \) | Flow index, dimensionless |
| \( \tau_{wp}, \tau_{wa} \) | wall shear rate in the pipe flow and annulus flow, Pa |
| \( v_{wp}, v_{wa} \) | average flow velocity in the pipe flow and annulus flow, m/s |
| \( \mu_{wp}, \mu_{wa} \) | wall effective viscosity of the fluid in the drilling string and annulus, Pa.s |
| \( D_{\text{eq}}, D_{\text{ea}} \) | equivalent diameter in the pipe flow and annulus flow, m |
| \( D_{\text{es}}, D_{\text{hy}} \) | ID of the drilling string and the hydraulics diameter, m |
| \( \text{Re}_{gp}, \text{Re}_{ga} \) | generalised Reynolds number in the pipe flow and the annulus flow, dimensionless |
| \( \gamma_{wp}, \gamma_{wa} \) | wall shear rate in the pipe flow and annulus flow, \( \text{s}^{-1} \) |
| \( \text{Re}_{gc}, \text{Re}_{gt} \) | laminar and turbulent flow Reynolds number at the critical state, dimensionless |
| \( e_{gt} \) | friction coefficients in the pipe flow and annulus flow, dimensionless |