EVALUATION OF AERATED DRILLING IN K-01 GEOTHERMAL WELL USING GUO GHALAMBOR’S GAS-LIQUID RATE WINDOW

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ABSTRACT

Common problem in geothermal drilling is loss circulation problem. One of the common methods to cure loss circulation problem is using Lost Circulation Materials (LCM), but in the production zone, using LCM can damage the production zone. Therefore, underbalanced drilling is method that can be used to prevent loss circulation problems in production zone in geothermal well. One of the most common underbalanced drilling methods is aerated drilling or foam drilling. Aerated drilling was used to overcome the loss of circulation problem in production zone in K-01 Geothermal Well. Even though, the aerated drilling was already used, but the loss circulation problem was still occurred. The purpose of this research is to evaluate aerated drilling operation in K-01 Well using Guo Ghalambor’s Gas-Liquid Rate Window and make recommended gas-liquid rate for the next drilling operation. Gas-Liquid Rate Window is constructed using characteristic of the formation, drilling parameters, daily drilling report and also fluid injection characteristics that was used for aerated drilling operation in K-01 geothermal well. Using the constructed Gas-Liquid Rate Window, an evaluation is carried out for the drilling operation in K-01 geothermal well. The gas-liquid rate parameters used in aerated drilling operations is evaluated while checking the loss circulation event from the mud logging data. After the evaluation of the aerated drilling is carried out in then a suggestion is made for the next drilling operation. Based on the evaluation, the combination of gas-liquid rates that was used on the 9.875”hole section in K-01 Well was in the outside of the constructed GLRW therefore loss circulation problem occurred. The recommended gas-liquid rate combination from this research can be used to determine the gas-liquid rate combination to prevent loss circulation problems, wellbore damage and cutting transport problems.

Keywords: Aerated drilling, geothermal, loss circulation.

INTRODUCTION

Drilling in geothermal well is a quite challenging operation. The problem is not only caused by high the temperature but also because of loss circulation problem. Loss circulation problem in geothermal well is usually caused by natural fractures and subnormal pressure reservoir [1]. The main target for geothermal drilling itself is the fault network and almost all faults network have low or subnormal pressure. If the loss circulation problem is not resolved, it can cause other problems such as stuck pipe[2]. Stuck pipe occurs because the drilling fluid, which has function to lift the drill cuttings to the surface, is lost to the formation and resulting in an accumulation of drill cuttings in the drill hole and causing a stuck pipe.

One of the common methods to cure loss circulation is using Lost Circulation Materials[3]. But in the production zone, using Lost Circulation Materials can damage the production zone. Therefore, using LCM in the geothermal production zone is not an option.

Underbalanced drilling is method that can be used to prevent loss circulation problems [1]. Formation damage can also be avoided using underbalanced drilling [4]. One of the most common underbalanced drilling methods is aerated drilling or foam drilling[5]. Aerated drilling is a drilling method that mix liquid phase (mud) and gas phase (air or nitrogen) to create underbalanced conditions in the wellbore[6].
But determining the gas-liquid rate in aerated drilling is not a simple thing. Because the combination of gas-liquid rate in aerated drilling is critical to prevent formation damage and borehole damage[5]. The gas-liquid rate combination also must consider the cutting carrying capacity [7]. The combination of gas-liquid rate should be sufficient enough to lift the cuttings while maintaining the underbalanced condition. Besides that, the complexity of water, oil, gas and solid multiphase flow in the system must be also considered [8].

Aerated drilling was used to overcome the loss of circulation issues in production zone in K-01 Geothermal Well. Even though, the aerated drilling was already used, but the loss circulation problem was still occurred. The purpose of this research is to evaluate the gas-liquid rate combination that was used in K-01 Well and give recommended gas-liquid rate for the next drilling operation.

AERATED DRILLING GAS-LIQUID RATE WINDOW (GLRW)

The use of aerated drilling in geothermal well can reduce the risk of drilling problems and the well productivity become better[9]. Aerated drilling can reduce circulation loss problems, increase Rate of Penetration, avoid differential pipe sticking, and prevent formation damage. Even so, some of the disadvantages that may be caused by the use of aerated drilling, such as the need for additional costs for compressor fuel, noise generated from the compressor, and corrosion problems cannot be ignored. Good planning before using aerated drilling techniques can cover these disadvantages because the final result brings many benefits to geothermal well drilling operations [9].

To determine the gas-liquid rate combination, Guo-Ghalambor introduced The GLRW concept. The combination of injection gas flow rate and drilling mud flow rate must be appropriately designed so that circulation-break-bottom hole pressure is bigger than formation collapse pressure and flowing-bottom hole pressure is smaller than formation pore pressure [8]. Besides, in designing aeration fluid, it is also necessary to consider the lifting capacity of drill cuttings from the fluid and wellbore washout. Gas-Liquid Rate Window (GLRW) is a combination of several factors considered in designing aerated drilling. Gas-Liquid Rate Window (GLRW) is consist of Collapse Pressure Limit, Balanced Pressure Limit, Cutting Carrying Capacity Limit and Wellbore Washout Limit.

Collapse Pressure Limit

The Collapse Pressure Limit (The Right Boundary) is the limit in the GLRW that maintain the static bottom hole pressure is greater than the formation collapse pressure. The static bottom hole pressure must be greater than the formation collapse pressure to prevent formation collapse in the borehole. The Collapse Pressure Limit is constructed using equation 1 until 5 [9]. The calculation of the bottom hole pressure in the vertical section can be done using equation 1. The constants $a''$ and $b''$ can be seen in equations 4 and 5.

\[ b''(P_{hy} - P_s) + \ln \left( \frac{P_{hy}}{P_s} \right) = a''H \]  

(1)

For directional wells, the calculation of bottom hole pressure for the angle-build up and the slant section of the well can be done using equations Equation 2 and Equation 3.

\[ b''(P_{hy} - P_s) + \ln \left( \frac{P_{hy}}{P_s} \right) = a''R \sin (I_m) \]  

(2)

\[ b''(P_{hy} - P_s) + \ln \left( \frac{P_{hy}}{P_s} \right) = a''S \cos (I_m) \]  

(3)

\[ a'' = \frac{9.45 \times 10^{-5}d_b^2S_Rp + 1.667 \times 10^{-2}W_m}{6.7846 \times 10^{-2}TQ_{go}} \]  

(4)

\[ ... + 9.7327 \times 10^{-2}S_fQ_f + 1.275 \times 10^{-3}S_b}{6.7846 \times 10^{-2}TQ_{go}} \]  

\[ b'' = \frac{2.2283 \times 10^{-3}Q_m + 1.5597 \times 10^{-3}Q_f}{6.7846 \times 10^{-2}TQ_{go}} \]  

(5)

Balanced Pressure Limit

The Balanced Pressure Limit (The Left Boundary) is the limit that maintain the flowing bottom hole pressure is lower than the formation pressure. The flowing bottom hole pressure must
be smaller than formation pore pressure in order to create underbalanced condition so the lost circulation can be prevented. The Balance Pressure Limit is constructed using equation 6 until 21 [9]. The calculation of frictional pressure loss can be done using equations 6 until 9. The goal seeks feature on the spreadsheet can be used to do the calculations.

\[
P_{fr} = P_{fr1} + P_{fr2} + P_{fr3}
\]

(6)

\[
b''(P_{fr1} - P_s) + \ln \left( \frac{P_{fr1}}{P_s} \right) = a''d''e''H
\]

(7)

\[
b'' \left( \frac{P_{fr2}^2 - P_s^2}{2} + \frac{P_{fr2} - P_s}{2} \right) = 2a''c''e''d''e''H
\]

(8)

\[
b'' \left( \frac{P_{fr3}^3 - P_s^3}{3} + \frac{1}{2} \left( P_{fr2}^2 - P_s^2 \right) \right) = a''c''e''d''e''H
\]

(9)

For directional wells, it is necessary to calculate the pressure due to friction in the angle-build-up and inclined sections. Equations 10 to 12 can be used for calculations on the angle-build-up section. Equations 13 to 15 can be used to calculate the slant section of the borehole.

\[
b'' \left( P_{fr1} - P_s \right) + \ln \left( \frac{P_{fr1}}{P_s} \right) = a''d''e''R_l m
\]

(10)

\[
b'' \left( \frac{P_{fr2}^2 - P_s^2}{2} + \frac{P_{fr2} - P_s}{2} \right) = 2a''c''d''e''R_l m
\]

(11)

\[
b'' \left( \frac{P_{fr3}^3 - P_s^3}{3} + \frac{1}{2} \left( P_{fr2}^2 - P_s^2 \right) \right) = a''c''d''e''R_l m
\]

(12)

\[
b'' \left( P_{fr1} - P_s \right) + \ln \left( \frac{P_{fr1}}{P_s} \right) = a''d''e''S
\]

(13)

Some of the constants required in the above calculations can be calculated using the following equation.

\[
A = \frac{\pi}{4} \left( d_o^2 - d_i^2 \right)
\]

(16)

\[
c'' = \frac{9.777T Q_g}{A}
\]

(17)

\[
d'' = \frac{0.33Q_m + 0.22Q_f}{A}
\]

(18)

\[
e'' = \frac{f}{2gD_h}
\]

(19)

\[
f = \left[ \frac{1}{1.74 - 2 \log \left( \frac{2e}{d_{mi}} \right)} \right]^2
\]

(20)

\[
\ddot{e} = \frac{e_i d_i + e_o d_o}{d_i + d_o}
\]

(21)

### Cutting Carrying Capacity Limit

The Cutting Carrying Capacity Limit (The Lower Limit) is the limit for cutting transport criteria. The gas-liquid rate combination have to be able to lift the cuttings in order to prevent stuck pipe. The Guo-Ghalambor method uses a minimum kinetic energy value of 3 lbf-ft / ft^3 for aerated fluid so that drill cuttings can be lifted to the surface. The Cutting Carrying Capacity limit is constructed using equation 22 until 26 [9].

The kinetic energy can be calculated using the following equation.

\[
E_m = \frac{1}{2} \gamma_m v_m^2
\]

(22)
The specific weight of the aerated fluid can be calculated using the equation 23.

\[
\gamma_m = \frac{a''P}{b''P + 1}
\]  (23)

**Equation 24** can be used to calculate the transport velocity.

\[
v_{tr} = \frac{\pi d_b^2}{4AC_p} R_p 3600
\]  (24)

The settling velocity of the drill cuttings can be calculated using the equation below.

\[
v_{sl} = v_m - v_{tr}
\]  (25)

\[
v_{sl} = 5.35 \sqrt{\frac{D_s(\rho_s - \rho_f)}{\rho_f}}
\]  (26)

**Wellbore Washout/ Equipment Limit**

The upper limit is made to avoid wellbore washout in the well when aerated drilling is carried out. There is no specific method that discusses the design of the upper bound, so each company has its standard in determining the upper limit of GLRW. The limitations of the drilling tool can be used to determine the upper limit of the GLRW[10]. The maximum standard of the fluid flow rate through the mud motor can be used in determining the upper limit of GLRW[10].

**METHODOLOGY**

The workflow of this research can be seen in Figure 1. The purpose of this research is to construct GLRW, evaluate the aerated drilling parameters on well K-01 and give recommendation for the next drilling operation.

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**Figure 1** Workflow for designing GLRW and evaluation of aerated drilling
The first step in designing Gas-Liquid Rate Window is collecting data that include characteristic of the formation, drilling parameters, daily drilling report and also fluid injection characteristics that was used for aerated drilling operation in K-01 geothermal well.

After the data are collected, the collapse pressure limit, balanced pressure limit, cutting transport limit, and wellbore washout limit must be constructed to create the Gas-Liquid Rate Window.

Using the constructed Gas-Liquid Rate Window, an evaluation is carried out for the drilling operation in K-01 geothermal well. The gas-liquidate parameters used in aerated drilling operations is evaluated while checking the loss circulation event from the mud logging data.

After the evaluation of the aerated drilling is carried out in then a suggestion is made for the next drilling operation. The suggestion is made based on the constructed GLRW in order to prevent drilling problems in the next drilling operation.

RESULT AND DISCUSSION

Gas-Liquid Rate Window Design

From the drilling prognosis, well K-01 was predicted to get through several lost circulation zones. At a depth of 4,002.6-8,202.1 ft-MD (3,543.3-6,663.4 ft-TVD), a total circulation loss zone would be found with a rate of more than 20 barrels/minute. The depth 5,905.5 – 9,714.5 ft-MD will be drilled with 9.875”hole size and will be the production zone of K-01 geothermal. With that rate of loss circulation, blind drilling can’t be used because it can cause stuck pipe. The LCM, or cement plug cannot be used because it will damage the formation. Therefore, aerated drilling is used in this section.

The formation that was penetrated was a formation that dominated by andesite breccias with metasediments inserts. The drilling mud that used was water-based mud with density 8.5 ppg.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit Diameter</td>
<td>db</td>
<td>9.875</td>
<td>in</td>
</tr>
<tr>
<td>Specific gravity of solid</td>
<td>Ss</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Rate of Penetration</td>
<td>Rp</td>
<td>20</td>
<td>ft/hr</td>
</tr>
<tr>
<td>Mud weight</td>
<td>Wm</td>
<td>8.5</td>
<td>ppg</td>
</tr>
<tr>
<td>Mud flow rate</td>
<td>Qm</td>
<td>300-900</td>
<td>gpm</td>
</tr>
<tr>
<td>Specific gravity of formation fluid</td>
<td>Sl</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Formation fluid influx flowrate</td>
<td>Qf</td>
<td>0</td>
<td>bbl/hr</td>
</tr>
<tr>
<td>Specific gravity of gas</td>
<td>Sg</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Volumetric flow rate of gas</td>
<td>Qgo</td>
<td>550-3,300</td>
<td>scfm</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>T</td>
<td>537</td>
<td>Rankine</td>
</tr>
<tr>
<td>Temperature at the point of interest</td>
<td>T</td>
<td>870</td>
<td>Rankine</td>
</tr>
<tr>
<td>Roughness inner wall (drill collar)</td>
<td>ei</td>
<td>0.0018</td>
<td>in</td>
</tr>
</tbody>
</table>

Table 1. Data for designing GLRW section 9.87” geothermal well K-01
The data that was used in the design process for the GLRW can be seen in table 1. Well K-01 is a directional well, so the calculation process was done by divided the well into vertical section, build-up section and tangent section.

Using variety of gas flow rate (from 550-3,300 scfm) and liquid rate (from 300 gpm – 900 gpm) combination, the bottom-hole pressure graph was constructed (Figure 2). The collapse pressure was used as the minimum pressure limit that will cause formation collapse. The study of the calculation of collapse pressure is outside the scope of this research, so based on the previous well, it was assumed that the value of collapse pressure is 6 ppg. At a depth of 7,760 ft-TVD, collapse pressure is 2,421.2 psia. The Bottom Hole Pressure in the grey area of figure 2 will cause the formation collapse.

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole roughness</td>
<td>eo</td>
</tr>
<tr>
<td>Surface choke pressure</td>
<td>Ps</td>
</tr>
<tr>
<td>Vertical depth</td>
<td>H</td>
</tr>
<tr>
<td>Radius of curvature</td>
<td>R</td>
</tr>
<tr>
<td>Slant section</td>
<td>S</td>
</tr>
<tr>
<td>Maximum inclination</td>
<td>Im</td>
</tr>
<tr>
<td>Solid diameter</td>
<td>Ds</td>
</tr>
<tr>
<td>Density of solid</td>
<td>ρs</td>
</tr>
<tr>
<td>Allowable cutting concentration</td>
<td>Cp</td>
</tr>
<tr>
<td>Final depth</td>
<td></td>
</tr>
<tr>
<td>Reservoir Pressure</td>
<td></td>
</tr>
<tr>
<td>Collapse Pressure</td>
<td></td>
</tr>
<tr>
<td>Standard motor flow range</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2** Breaking BHP (psia) vs Gas Injection Flow Rate (scfm)

The intersection points between the static bottom hole pressure and the collapse pressure limit can be seen in Table 2 and then it would be used to construct the Collapse Pressure Limit of the GLRW.
The graph of flowing bottom hole pressure vs gas injection flow rate can be seen in Figure 3. The formation pressure is 8 ppg. At 7,760 ft-TVD the formation pressure is 3,228.21 psi. The formation pressure was used as the limit for underbalance condition. The bottom hole pressure should be maintained in the grey area on the Figure 3 to maintain the underbalanced condition.

The value of 3 ft-lb/ft³ is used as the minimum kinetic energy needed to lift the drill cuttings. From the gas-liquid rate combination, the kinetic energy value was generated as can be seen in Table 4.

Table 2 Collapse Pressure Limit

<table>
<thead>
<tr>
<th>Qm (gpm)</th>
<th>Qg (scfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1100</td>
</tr>
<tr>
<td>400</td>
<td>1500</td>
</tr>
<tr>
<td>500</td>
<td>1850</td>
</tr>
<tr>
<td>600</td>
<td>2200</td>
</tr>
<tr>
<td>700</td>
<td>2550</td>
</tr>
<tr>
<td>800</td>
<td>2920</td>
</tr>
<tr>
<td>900</td>
<td>3240</td>
</tr>
</tbody>
</table>

Table 3 Balanced Pressure Limit

<table>
<thead>
<tr>
<th>Qm (gpm)</th>
<th>Qg (scfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>750</td>
</tr>
<tr>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>500</td>
<td>1300</td>
</tr>
<tr>
<td>600</td>
<td>1600</td>
</tr>
<tr>
<td>700</td>
<td>1850</td>
</tr>
<tr>
<td>800</td>
<td>2150</td>
</tr>
<tr>
<td>900</td>
<td>2490</td>
</tr>
</tbody>
</table>

Table 4. The results of the calculation of kinetic energy (Eg) for each combination of fluid flow rates

<table>
<thead>
<tr>
<th>Mud Injection Flow Rate (gpm)</th>
<th>Kinetic Energy (Eg, ft-lb/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>15. 27. 41. 59. 79. 103</td>
</tr>
<tr>
<td>400</td>
<td>7. 0. 5. 0</td>
</tr>
<tr>
<td>500</td>
<td>110. 18. 29. 44. 62. 83. 107</td>
</tr>
<tr>
<td>600</td>
<td>0. 4. 9. 7. 6. 6</td>
</tr>
<tr>
<td>700</td>
<td>165. 23. 34. 49. 67. 88. 113</td>
</tr>
<tr>
<td>800</td>
<td>0. 3. 4. 1. 2. 5</td>
</tr>
<tr>
<td>900</td>
<td>220. 31. 41. 55. 73. 94. 119</td>
</tr>
<tr>
<td>100</td>
<td>0. 9. 4. 5. 4. 7</td>
</tr>
<tr>
<td>110</td>
<td>275. 45. 52. 64. 81. 102. 127</td>
</tr>
<tr>
<td>120</td>
<td>0. 9. 1. 6. 7</td>
</tr>
<tr>
<td>130</td>
<td>330. 66. 67. 77. 93. 113. 137</td>
</tr>
<tr>
<td>140</td>
<td>0. 3. 9. 5. 0</td>
</tr>
</tbody>
</table>

Figure 3 Flowing BHP (psia) vs Gas Injection Flow Rate (scfm)

The intersection points between the flowing bottom hole pressure and the formation pressure limit can be seen in Table 3 and then it would be used to construct the Balanced Pressure Limit of the GLRW.
The upper limit of GLRW can be determined from the formation washout pressure or the specifications of the equipment used. Because the value of pressure that causes the washout is unknown, the maximum fluid flow rate in the mud motor was used to determine the upper limit of GLRW. From the specifications of the mud motor used, the fluid flow rate is in the range of 300-900 gpm. The maximum value of this range became the upper limit of the GLRW. When the flow rate exceeds this value, there is a risk of damaging the mud motor.

After designing the right boundary, the left boundary, the upper limit and lower limit, the resulting GLRW is shown in Figure 5. Based on the GLRW, the aerated drilling operation work area is at gas injection flow rate 750-2,240 scfm and mudflow rate 300-900 gpm.

**Figure 4** GLRW of Well K-01 Hole Section 9.875"

**Evaluation of Aerated Drilling Parameters**

The gas injection will be started when the loss of circulation rate is greater than 3 barrels/minute (based on the K-01 Company Rules). In the 9.875"hole section drilling operation, circulation loss began to occur at 2,060 m-MD. As the depth increased, the rate of lost circulation increased. The aerated drilling was started at 2,490 m-MD, when the loss circulation rate reached 9.7 barrels/minute. The injected gas-liquid rate combination is 600 scfm and 800 gpm. Furthermore, the gas flow rate was gradually increased to 1,600 scfm. Several gas-liquid rate combinations that was used from 2,490 m-MD to 2,961 m-MD were plotted on the GLRW graph, and can be seen in Figure 5.

**Figure 5. Plot of Combination of Mud Flow Rate and Actual Injection Gas Flow Rate in GLRW**

Gas injection with a flow rate of 600 scfm was carried out at a depth of 2,490 m-MD. Furthermore, as the depth increases, the gas flow rate is increased to reach 1,600 scfm at the final depth of the hole section 9.875", while the mudflow rate is 724 gpm. As can be seen in Figure 5, the bottom-hole pressure that was resulted from the gas-liquid rate combination is greater than the formation pressure (outside of the GLRW). The Bottom-hole pressure was on the left side of the balanced pressure limit, so the wellbore condition was overbalance. The flowing bottom-hole pressure is greater than the formation pressure (3,228.21 psi).

Based on the mud logger report, even though the aerated drilling was used the lost circulation problem was still occurred at 7,760 ft-TVD with a loss of circulation rate of 11 barrel/minute. From that information, it is confirmed that the gas-liquid rate that used is outside the GLRW therefore the lost circulation problem occurred.

Based on the constructed GLRW, in order to achieve an underbalanced condition with the mudflow rate of 800 gpm, the gas injection rate that can be used is in the range 2,150-2,920 scfm.

**CONCLUSION**

The combination of gas-liquid rates (724 gpm and 1,600 scfm) that was used at the final depth of 2961 m-MD on the 9.875"hole section in K-01 Well was in the outside of the constructed GLRW therefore loss circulation problem occurred. The combination of gas-liquid rate
used was on the left side of the GLRW limit, hence creating overbalance condition. The recommended gas-liquid rate combination based on the constructed GLRW is 300-900 gpm and 750-3,240 scfm. The constructed GLRW can be used to determine the gas-liquid rate combination to prevent loss circulation problems, wellbore damage and cutting transport problems.

REFERENCES


Nomenclature

\( A = \) Annulus area (in\(^2\))

\( C_p = \) Cutting concentration in annulus (\%)

\( D_H = \) Annulus diameter (ft)

\( D_s = \) Cuttings Diameter (ft)

\( d_b = \) Bit Diameter (in)

\( d_i = \) Annulus inner diameter (in)

\( d_o = \) Annulus outer diameter (in)

\( E_m = \) Kinetic Energy (lbf·ft/ft\(^3\))

\( e_i = \) Roughness of inner annulus (in)

\( e_o = \) Roughness of outer annulus (in)

\( \bar{e} = \) Average roughness (in)

\( f = \) Moody’s friction factor

\( f_l = \) Liquid volume fraction

\( g = \) gravitational acceleration (32.2 ft/s\(^2\))

\( H = \) Depth (ft)

\( I_m = \) Maximum inclination (radians)

\( P_{fr1} = \) Frictional pressure 1 (lb/ft\(^2\))

\( P_{fr2} = \) Frictional pressure 2 (lb/ft\(^2\))

\( P_{fr3} = \) Frictional pressure 3 (lb/ft\(^2\))

\( P_{fr} = \) Pressure loss due to friction (lb/ft\(^2\))

\( P_{hy} = \) Hydrostatic pressure (lb/ft\(^2\))

\( P_c = \) Choke pressure (lb/ft\(^2\))

\( Q_f = \) Volumetric Influx flowrate (bbl/hr)

\( Q_{go} = \) Volumetric gas flowrate [60 °F, 14.7 psia] (scfm)

\( Q_m = \) Volumetric mud flowrate (gpm)

\( R = \) Radius of Curvature (ft)

\( R_p = \) Rate of Penetration (ft/hr)

\( S = \) Length of slant section (ft)
$S_g =$ Gas specific gravity (air = 1)
$S_l =$ Influx specific gravity (water = 1)
$S_s =$ Cuttings specific gravity (water = 1)
$T =$ Temperature (Rankine)
$v_m =$ fluid mixture velocity (fps)
$v_{tr} =$ transport velocity (fps)
$v_{sl} =$ terminal settling velocity (fps)
$W_m =$ Mud Weight (ppg)
$\rho_s =$ Cuttings density (lbf/ft$^3$)
$\rho_g =$ Gas density (lbf/ft$^3$)
$\rho_f =$ Influx density (lbf/ft$^3$)
$\gamma_m =$ Specific weight of fluid mixture (lbf/ft$^3$)