Hydraulics and wellbore cleaning

01 Hydraulics & wellbore cleaning Introduction

1.0 Drilling fluid essentials

1.1 Objectives

The objectives of this section are to;
1. Present the key aspects of hydraulics and hole cleaning
2. Introduce drilling engineering terms and definitions used
3. Discuss drilling hydraulics and hole cleaning calculation methods required to understand essential drilling fluid mechanics and dynamic principles.

1.2 Introduction

In drilling fluids the term drilling hydraulics and hole cleaning refers to drilling operational functions where the fluid is used to both transfer fluid flow and pressure properties;

• through the surface pipe work
• through the drillstring and bottom hole components to the bit
• expend a pressure drop across the bit i.e. to optimize the rate of penetration
• to clean the bits cutters and area ahead of the bit
• to evacuate and transport the cuttings thereby preventing agglomeration and re-grinding of cuttings on the bit face and body.
• to transport cuttings efficiently and effectively out of the wellbore

For the drilling fluid to perform many of these functions e.g., transport cuttings effectively and efficiently to surface, the pumping system must be capable of overcoming the accumulated pressure losses associated with the surface equipment, the drillstring, the bit, the annulus and still deliver an efficient flow rate to effectively transport the cuttings out of the wellbore. The pressure losses that exist (particularly in the annulus) will also affect the total pressure exerted by the fluid column on the wellbore, potentially raising loss of circulation, kick control, and other wellbore stability issues.

The purpose of this hydraulics and hole cleaning section is thus to provide drilling operational and engineering persons with both the fundamental and necessary knowledge understanding, equations and procedures to perform a detailed performance and optimisation analysis of the hydraulic and hole cleaning capabilities of the circulating system.

Because rheology of the drilling fluid directly affects the circulating system pressure losses, the more accurately a model is selected and used, then the more precise the hydraulic analysis can be. The next section therefore provides a description of the common rheological models used to describe drilling fluids.
1.3 Fluid Rheology

1.3.1 Rheology Introduction

Rheology is the scientific study of the deformation and flow characteristics of matter. In respect to drilling fluids rheology deals with the relationships and analysis of:

- fluid flow rates and flow pressure
- combined influence on the flow characteristics of the fluid
- viscosities and hole cleaning capabilities
- pressure loss, pressure management and in particular equivalent circulating densities (ECD).

With respect to drilling operations and well engineering, rheology analysis allows the hydraulics and hole cleaning properties of a fluid system to be fully determined and evaluated.

1.3.2 Velocity profile

Figure one presents laminar and turbulent fluid flow velocity profiles within a cylindrical pipe. In both cases forces will exist within the fluid to resist fluid flow. Forces i.e. shear stresses that are analogous to the friction arising when one fluid layer moves past another layer. In the case of laminar flow it can be viewed that the fluid velocity increases progressively away from the walls to a maximum near the centre of the annulus. This results as it is easier for each fluid layer to move past another fluid layer than to move past the walls. The rate at which a fluid layer moves past another is termed the shear rate.

**Experiment:** Take a rod and stir it in a glass of water. Note how the action of stirring causes a velocity gradient to be created in the fluid i.e. higher at the rod than at the outer surface of the glass. Imagine now that the fluid was cold thick oil (i.e. with a high viscosity). A greater force would now be required to stir i.e. indicating the higher shear stress in the cold oil.

![Fig 1: Velocity profiles for pipe flow](image)

1.3.2 Shear stress ($\tau$) and shear rate ($\gamma$)

**Shear stress ($\tau$)**

As a fluid moves, the shear stress ($\tau$) is the resulting effect required to slide one unit area layer of a substance over another and then sustain a particular type of fluid flow. e.g. In laminar flow, the shear stress is the frictional drag that exists between individual laminae. The magnitude of shear stress will depend on the viscosity of the fluid.

Thus Shear stress ($\tau$) = \( \frac{\text{Force}}{\text{area}} \).

The symbol used for Shear stress is the Greek letter Tau ($\tau$).

Field units = lb/ft\(^2\)  \quad \text{SI Units} = \text{N/m}\(^2\) \text{ or more commonly in fluid calculations as Dynes/cm}^2\)

In common fluids such as oil and water the magnitude of shear stress is directly proportional to the change of velocity between different positions of the fluid as illustrated in figure 2 in the following page.
In figure 2, the concept of velocity change in a fluid is shown by a thin layer of fluid between two surface boundaries. One which is stationary e.g. the casing boundary, while the other is moving e.g. the drillstring boundary.

In this situation it is important to note the fundamental condition that exists when a real fluid is in contact with a boundary surface, i.e. that the fluid has the same velocity as the boundary.

In summary therefore zero velocity would exist at the casing wall boundary and at the drillpipe wall boundary, fluid would have a velocity ($\nu$).

From figure 2 if the distance between two small surfaces is small, then the rate of change of velocity with position ($y$) is linear, i.e. in a straight line manner.

As the velocity gradient in fig 2. could thus be defined as a measure of the velocity change i.e. $\Delta \nu/\Delta y$. This is called the shear rate.

**Shear rate**

Shear rate ($\gamma$) is the relative velocity of one lamina moving relative to adjacent lamina, divided by the distance between then. Ref figure 3.

Shear rate ($\gamma$, sec$^{-1}$) = $\text{Velocity (cm/sec)} / \text{distance (cm)}$.

The symbol used for Shear rate is the Greek letter Gamma ($\gamma$).

**Field units** = (ft/sec) / ft  \hspace{1cm} **SI Units** = (cm/sec) / cm

Both units expressed in sec$^{-1}$ (reciprocal seconds)

**Note:** 1sec$^{-1}$ = 1.703·RPM (where RPM is the speed of the fann viscometer.)
1.4 Flow regimes. The mud flow in the various parts of the circulating system will be either laminar, transitional or turbulent depending on the magnitude of a dimensionless number that indicates the type of flow present, i.e. the Reynolds number (NR). In hydraulics and hole cleaning the evaluation of drilling fluids are considered to be in either laminar or turbulent flow. The flow regime present dependent upon the flow rate (fluid velocities), flow pressure (forces required), and the borehole, drillstring geometrical clearance (that can effect both pressure and velocity effects).

1.4.1 laminar flow. Laminar flow occurs when the individual flow layers (laminae) slide past each other with a minimum of mixing. Figure 1.4 demonstrate laminar flow regime in a pipe or drilling annulus. Generally, laminar flow is the preferred annulus flow profile because it results in less pressure loss, reduced hole erosion, enlargement or washout.

To achieve efficient cutting transport in laminar flow, the fluid rheology should however be tailored to give a flatter velocity profile therefore avoiding excessive cuttings slip near the borehole wall and drill pipe.

1.4.2 Transitional flow Transition flow occurs where laminar flow can no longer exist due to the increased momentum forces as the fluid goes into turbulence as velocity further increases. This is sometimes referred to as "unstable turbulence". A calculated and defined Reynolds number range can help to define such transition velocities.

1.4.3 Turbulent flow Turbulent flow occurs when the fluid is constantly swirling and eddying as it moves through the flow channel. Pressure losses within a circulating system increase as the degree of turbulence increases. Additionally, in turbulence the viscous properties if the mud no longer have an effect on cuttings removal efficiency. Only the momentum forces of mud; i.e. weight and predominantly velocity, affect hole cleaning in turbulent flow. In turbulent flow, the fluid velocity at the walls is zero; however, the velocity profile within the stream is essentially flat. This flat profile improves hole cleaning characteristics but, at the expense of increased pressure losses through fluid turbulence. Highly turbulent flow may also erode a soft formation (washout) which can reduce cuttings removal efficiency, increase cementing volumes, prevent zonal isolation, and effect wire line log quality. Generally, turbulent flow in softer to medium strength formations should be avoided if hole instability, washout and pressure effects may be a concern.
2.0 Hydraulics and hole cleaning analysis.

Hydraulics programs have generally the options of using a selection of the fluids models available to evaluate the detailed hydraulic calculations that are required in pre-planning, execution and post well review phases of drilling a well. The usual hydraulics analysis makes use of either the Power Law, Modified power law and/or Herschel Bukley models.

The objective of a hydraulics analysis is however to essentially assess the effects of the viscosity of the drilling fluid on certain critical drilling parameters. The following drilling parameters are evaluated in the hydraulics and hole cleaning analysis.

2.1 Parameters

1. Determining annular pressure losses to establish equivalent circulating density (ECD). *Note: ECD is important for prevention fracturing the weakest formations in the well and then the loss of circulation that could result.*
2. Assessing the effects of fluid changes on the system's hydraulic performance. *e.g. changes in mud weight.*
3. Optimizing hydraulics for enhanced drilling performance. *e.g., increased ROP, bit/bottom hole cleaning.*
4. Ensuring good hole cleaning *e.g. cuttings transport and concentration in the annulus.*
5. Preventing borehole erosion from turbulent flow in the annulus. *e.g. particularly around drill collars and bottom hole assembly components.*
6. Preventing borehole instability and pressure control problems from pulling pipe too fast *e.g. swabbing pressures reducing wellbore pressure where instability may result.*
7. Preventing loss of circulation from running pipe too fast *e.g. pressure surging greater than formation fracture pressures.*

2.2 Hydraulics and hole cleaning process

Introduction.

Removal of cuttings from the wellbore *i.e. hole cleaning* is an essential part of drilling operation. Efficient hole cleaning must therefore be maintained during all wellbore sections drilled. Failure to effectively transport the cuttings can result in a number of drilling problems including:

- Inadequate bit/bottom hole cleaning and reduced ROP
- Fines generation and cuttings beds build up in th wellbore
- Increased equivalent circulating densities
- Deterioration of wellbore quality.
- Deterioration in mud properties
- Inefficient solids removal (due to fines generated in nud)
- Excessive overpull on trips
- High rotary torque leading to;
- Stuck pipe, Hole pack-off, Formation break down, Lost Circulation
- Often ultimately requiring to side-track and re-drill the wellbore

All of these are potential problems for both near vertical *i.e. less than 30degrees inclination* and extended reach drilling *i.e. ERD wells*. The problems listed above are more common on highly deviated wells as it is here that cuttings are more difficult to transport and remove from the wellbore. Successful hole cleaning therefore relies upon integrating rig and downhole equipment, optimum mud properties with best drilling practices.

When difficulties are encountered it is essential to understand the root nature, cause and potential effect of a potential problem where drilling data will testify that minimal prevention is generally preferred to the more costly and time consuming cure that may then result.
2.3 General Factors Effecting Hole Cleaning

2.3.1 Drilling variables
There are a large number of drilling variables which influence the hole cleaning process. Some variables the driller has a direct control on, others are pre-determined by the constraints of the drilling operation.

Annular Velocity, Mud Properties and bit bottom hole cleaning are viewed as the major variables in the process of hole cleaning the solids from the wellbore during drilling and tripping (Ref table 1 below). They are however only one part of an integrated process to achieving full hole cleaning optimisation. Other variables if not fully examined, evaluated and considered will result in a damaging effect on other well processes. E.g. Drilling and cost efficiency, bit/bottom hole cleaning, solids removal, wellbore stability, stuck pipe and hole problem prevention.

Table 1; Hole cleaning variables.

<table>
<thead>
<tr>
<th>Hole cleaning (transport) variables</th>
<th>Major</th>
<th>Moderate</th>
<th>Minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annular velocity*</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mud rheology</td>
<td>✓</td>
<td>✓ (vertical &amp; horizontal wells)</td>
<td>✓ (high angle)</td>
</tr>
<tr>
<td>Bit &amp; bottom hole cleaning</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Cuttings-size, shape, density</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mud weight</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mud type (water based)</td>
<td>✓</td>
<td>✓ (OBM &amp; synthetic)</td>
<td></td>
</tr>
<tr>
<td>Pipe reciprocation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pipe rotation (mode, speed, effect)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Drillstring &amp; hole size</td>
<td>✓</td>
<td>✓ (&lt;17.5' hole)</td>
<td>✓ (&gt;17.5' hole)</td>
</tr>
<tr>
<td>Hole and pipe eccentricity</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drilling rate</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Drilling operation (Rotary)</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Drilling operation (Sliding)</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

* Annular velocity is determined by (flowrate, wellbore and drillstring geometry.)

In reality a compromise of all hole-cleaning variables, in the well planning, engineering and operational circumstances must be investigated and accounted for. Engineers must use necessary well engineering design and planning tools, offset information, and consider specific rig and down hole equipment aspects to be able to best develop the most suited balance of drillstring / bottom hole assembly configurations to be run.

Hole sizes, hole angle, casing setting depths, well conditions and formation characteristics must also be suitably planned, engineered and accounted for. The following 'rule of thumb guidelines' that can be found in other e-shop files have therefore been compiled to support hole cleaning in the well planning and operational phases of drilling operations.
2.3.2 Cuttings Transport

Figure 5 opposite represents a schematic of the cuttings transport mechanisms for a range of well inclinations. Ref. BP Exploration circ hole problem data package.

In wellbore inclinations less than 30 degrees, it can be seen that the cuttings are effectively suspended by the fluid shear and cuttings beds do not form i.e. zones 1 and 3. For such cases conventional transport calculations based on vertical slip velocities are applicable.

Generally for shallow angles i.e. 10 - 30 degrees inclination, annular velocity requirements are typically 20-30% in excess of vertical wells.

At well inclinations > 30 degrees the cuttings can now form beds on the low side of the wellbore that may under certain circumstances and conditions slide or even avalanche back down the well, causing the annulus to pack-off. Cuttings that form on the low side of the hole can either move en-masse as a sliding bed i.e. zone 4 or alternatively may be transported at the bed/mud interface as ripples or dune i.e. zone 2.

Flow patterns in the annulus therefore depend strongly upon flow rate and mud rheology. Thin fluids with low YP's tend to promote turbulence and cuttings saltation. Thick fluid with high YP's increase the fluid drag force and causes the cuttings bed to slide.

The ideal zones for cuttings transport are therefore Zones 1 and 2. Zone 5 (no hole cleaning) will virtually guarantee drilling, tripping casing, cementing and wellbore related problems.

2.3.3 Rheology

The effect of mud rheology on hole cleaning depends on the annular flow regime. In the laminar regime, increasing mud viscosity will improve hole cleaning and it is particularly effective if the low shear rheology and YP/PV ratio are high. In the turbulent regime reducing mud viscosity will help remove cuttings.

2.3.4 Yield Stress

This is a measure of the low shear properties of the mud. This property controls the size of cuttings which can be suspended by the flowing mud (dynamic suspension). The dynamic suspension will be affected by cuttings size and mud density. In practice the optimum level required is best established based on field data and experience.

2.3.5 Pump Rate

The mud flow rate provides the lifting force on cuttings to carry them out of the well. In highly deviated wells mud flow rate is the most important factor for hole cleaning. For vertical wells the rate of cuttings removal increases with increasing annular velocity and/or increased rheology.

2.3.6 Hole Geometry

Hole diameter has a very significant effect on annular velocity. Reducing hole diameter from 17.5 to 16 inch will for example increase annular velocity by approximately 20%.
2.3.7 Mud weight.
Mud weight influences hole cleaning by affecting the buoyancy of the drilled cuttings. As mud weight increase, the cuttings will tend to ‘float’ out of the well making hole cleaning easier. In practice the mud weight window will be constrained by other drilling factors other than hole cleaning. e.g. wellbore stability, equivalent circulating density, preventing losses and wellbore kicks etc.

2.3.8 Cuttings Properties
Hole cleaning is dependent upon both cuttings size and density. Increasing size and density both tend to increase the cuttings’ slip velocity. This makes transport more difficult. The effects of higher slip velocity can be combated by an appropriate increase in yield stress and mud gel. In extreme circumstances bit selection can be used to generate smaller cuttings and, hence, reduce slip velocity.

2.3.9 Rate of Penetration
Increases in penetration rate result in a higher cuttings concentration in the annulus. This will lead to a higher effective mud density in the annulus and higher circulating pressures which may, in turn, limit flow rates. With today’s technologies (better mud motors, bits, top drives) and higher capacity drilling equipment available (7500psi mud pumps, top drives etc.) There are often situations and circumstances where rates of penetrations must be controlled. In hole cleaning terms there is only two simple rules.

1. Do not drill a wellbore faster than it can be cleaned.
2. Do not drill a hole that cannot be readily tripped or cased.

2.3.10 Drillpipe Rotation
In deviated wells high pipe rotation speeds provide an effective means of mechanically disturbing cuttings beds and reintroducing them into the main mud flow for removal.
1. Downward rotation is most preferred.
2. Stationary rotations will have a less limited effect.
3. Upward rotation (back-reaming) is the least effective method to disturb cuttings, can cause further hole enlargement and should be applied only as a last resort.
4. Drillpipe rotations has least effect in vertical wells.
5. In a horizontal wellbore unwarranted rotation should be avoided if possible to optimise wellbore quality, minimize formation damage incurred.

Note: Point 3 is perhaps a very contentious issue in the industry today where there are often two distinct train of thought. However from this authors opinion it is the field data and technical premise that evaluates, and best substantiates the hard facts that the most efficient wells are where minimal reaming and backreaming has been applied. Secondly all technical merits support items 1-3 in rotational order of merit.

2.3.11 Rig Site Monitoring
There are a number of rig-site indicators that should be used to monitor the hole condition and allow preventative action to be taken at earliest opportunity. These should normally be examined for tends and sudden departures rather than absolute values.

The shape and size of the cuttings coming over the shaker should be regularly monitored. Small rounded cuttings indicate that cuttings have been spending extended periods downhole being reground by the BHA.
The cuttings return rate at the shakers should also be measured and compared with the volume predicted from the ROP. Simple devices are available to automate the measurement. Torque and drag can be used to determine whether cuttings beds are adding to the wellbore friction. Simulations should be conducted in advance using simulator readily available today. Deviations from the normal trend line can be indicative of cuttings bed forming. Erratic signal in torque or standpipe pressure can also be an early warning of cuttings beds.
3.0 Vertical and Near Vertical Wells

Rheology plays a very important role in transporting cuttings in vertical and near-vertical holes. Large diameter holes, in particular, cannot be cleaned by velocity alone. However, assuming that the mud has the correct rheology, hole cleaning on these wells is not normally a problem. The mud annular velocity is generally far greater than the cuttings slip velocity and so the cuttings are carried out of the hole. To ensure that a low slip velocity is achieved these wells are usually drilled with viscous, high yield point muds.

3.1. Hole Cleaning in Near Vertical Wells - Guidelines

Select mud properties to provide optimum hole cleaning whilst drilling.

Optimum properties will depend upon available pump rate, minimum and maximum flow rates derived from penetration anticipated.

In all cases mud rheology should be maintained at a level that will reduce slip velocity to acceptable levels. Specific requirements for annular velocity and cuttings slip velocity can be obtained within drilling fluids engineering software packages available.

Poor hole cleaning will result in high cuttings loading in the annulus. When circulation is stopped these cuttings can fall back and pack-off the BHA. When packing-off occurs this means the flow rate is too low or the well has not been circulated for sufficient time (assuming that the above criteria for mud properties has been met).

Circulate the hole thoroughly prior to tripping - *a single bottoms-up is not sufficient*. The minimum recommended volume for vertical wells is 1.3 x bottoms-up (1.5 for hole > 8½”). Monitor the shakers to ensure the cuttings return rate is reduced to an acceptable background level prior to commencing tripping.

**Limit use of high viscosity pills** to supplement hole cleaning. Rather adjust the properties of the active mud in circulation to provide optimum cleaning capacity. High weight pills should not be used in vertical wells.

For vertical holes *reciprocate rather than rotate the pipe* during circulation prior to tripping - this helps remove cuttings from stagnant zones near the wellbore wall.

Pulling through tight spots is OK provided the pipe is free going down. Agree a maximum allowable overpull in advance with the Company Man/Drilling Superintendent. Do not go immediately to the maximum overpull, but work up progressively ensuring that the pipe is free to go down on every occasion.

Stop and circulate the hole clean if over-pulls become excessive.

**Avoid precautionary backreaming**. It is more important to understand and consider the nature, causes and effect of any drilling, or tripping problems encountered before initiating backreaming often as a matter of course rather than purpose! Therefore bearing in mind that field data and engineering premise can support preferred best practices. Backreaming should only be initiated when absolutely necessary. *i.e. as a last resort.*
4.0 High Angle, Extended-Reach Wells (ERD)

Much of the information given above relating to hole cleaning in near vertical wells is also relevant to ERD wells. However it is far more difficult to maintain clean hole in deviated wells. The guidelines given below are based on the conclusions derived from both laboratory and field data:

4.1 Hole Cleaning in Deviated Wells - Guidelines

4.1.1 Flow Rate

The single most important factor relating to hole cleaning in deviated wells is flow rate (i.e. annular velocity). During directional drilling operations, drilled cuttings will settle on the low side of the hole and form a stationary bed if insufficient annular fluid velocity is used. The critical flow rate (CFR) required to prevent cuttings bed formation can be determined from Hole Cleaning Models and software packages that exist. Typical recommended flowrate are provided in table 2 opposite.

When planning a well it is imperative that mud pumps of sufficient size and capacity are selected to achieve this required rate. Typically few hole cleaning problems exist in vertical or horizontal sections. Most problems associated with hole cleaning are seen on deviated wells occur in the 50 - 60 deg section where gravity effects can cause cuttings beds to slump down the hole. Again wellbore software packages should be able model these effects and should be used in the planning of all wells and in particular Extended Reach applications.

4.1.2 Selection of Flow Regime

When correctly designed, both laminar and turbulent flow regimes will effectively clean a deviated well. In general increasing the viscosity of a fluid in laminar flow will improve hole cleaning as will a reduction of the viscosity of a fluid in turbulent flow. It is important that one/or the other regime is selected and that the transition zone between the two is avoided (Figure 3), generally viscous fluids in laminar flow are preferred because;

- Viscous fluids give better transport in the near-vertical sections.
- Viscous mud has better suspension characteristics when circulation is stopped.

It is difficult to achieve “turbulent flow” except in small hole sizes.

Turbulent flow effectively prevents the formation of cuttings beds on the low side of highly deviated wells and helps to minimise ECD. For these reasons turbulence may be preferred in deviated holes where there is a small window between mud weight and fracture gradient. It is however, difficult to achieve turbulence in large diameter holes (12.25” and greater) particularly when weighted muds are being used. Turbulent regimes should not be used in friable, non competent formations. Subsequent wash-out of the rock will reduce annular velocities to a point where laminar flow will develop in a fluid with properties specifically designed for turbulence. Cuttings bed formation and barite sag will almost inevitably follow. Effectively the same process can occur as the fluid, designed for turbulence in small diameter hole, enters larger diameters further up the hole. All fluids designed for turbulence must have, as a minimum, sufficient suspension characteristics and carrying capacity to clean these larger hole (casing) sizes.

<table>
<thead>
<tr>
<th>HOLE SIZE</th>
<th>TYPICAL FLOW RATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 1/2”</td>
<td>1100 gpm minimum</td>
</tr>
<tr>
<td></td>
<td>Some rigs achieve</td>
</tr>
<tr>
<td></td>
<td>1250 - 1400 gpm</td>
</tr>
<tr>
<td>12 1/4”</td>
<td>Aim for 1100 gpm</td>
</tr>
<tr>
<td></td>
<td>(although 800 - 1000 gpm is typically achieved)</td>
</tr>
<tr>
<td></td>
<td>If 1000 gpm is not achievable, ensure tripping procedures are in place for poorly cleaned hole.</td>
</tr>
<tr>
<td>8 1/2”</td>
<td>Aim for 500 gpm</td>
</tr>
</tbody>
</table>
4.1.3 Mud Rheology
Experience has shown that good mud rheology is extremely important to hole cleaning when drilling a high angle well. Studies show that the effects of mud rheology and annular flow regime are mutually dependent. In the laminar regime, increasing mud viscosity will improve hole cleaning and this is particularly effective if the Yield Stress is high. In the turbulent regime, however, reducing mud viscosity will help removing cuttings. Therefore, the mud rheology should be designed to avoid the transitional flow regime. For hole sizes above 8.5", the annular flow is laminar under most circumstances. Therefore it is desirable to specify a minimum Yield Stress. In practice the optimum level required is best established based on field data and experience.

4.1.4 Hole Cleaning Charts
A series of Hole Cleaning Charts have been developed which can be used to determine the Critical Flow Rate for various hole sizes when drilling a deviated well. These charts, with examples, are included in another separate worksheet.

4.1.5 Hydraulics
Conventional drilling hydraulics rely upon optimising hydraulic horsepower or hydraulic impact at the bit. This requires approximately 65% of the system pressure loss to be dissipated at the bit. For ERD wells where the flow rates for hole cleaning are higher, a compromise and reduction of energy spent at the bit is required otherwise flow-rates required to clean the wellbore cannot be achieved. This is achieved by selecting larger nozzle diameters yet not compromising on requirements to clean the bit and bottom of the wellbore as per bit manufacturers recommendations or field operating knowledge and experience.

The distribution of pressure losses throughout the circulating system depends upon well geometry and fluid properties. In conventional drilling the annular pressure drop is generally <5% of the overall system loss (this proportion increases dramatically for slim-hole configurations). The annular pressure loss, whilst only a small fraction of the total loss is critical for determining ECD.

4.1.6 Use of Mud Pills
Proper use of mud pills may improve hole cleaning in a high angle well. High viscosity (preferably weighted) pills are often effective in hole sizes larger than 8½” whilst low viscosity pills are beneficial in smaller holes. When using a low viscosity pill, it is important to maintain the normal high flow rate and minimise the stagnant circulation time. Also it is often necessary for a low viscosity pill to be followed by a high viscosity (weighted) pill in order to ensure adequate hole cleaning in the larger vertical hole section. The specific pill volumes should be determined based on the hole size and the calculated effect on hydrostatic head.

4.1.7 Steady ROP
A higher ROP requires a higher flow rate to clean the hole. It is a good practice to drill the hole with a steady ROP and select the required flow rate for hole cleaning accordingly. In cases where this can not be achieved, the average ROP over a 30 m (100 ft) interval should be used to select the flow rate.

4.1.8 Drillpipe Rotation/Reciprocation
Experience has shown that drillpipe rotation/reciprocation is very effective in improving hole cleaning, in particular at high speeds. This is because the drillpipe rotation/reciprocation will mechanically agitate the cuttings bed and therefore help removing cuttings. Discuss limitations of rotary speeds when using downhole motors with the directional drilling company.

4.1.9 Large Surface Hole Section
When drilling ERD wells, it is often necessary to kick off in the large surface hole section (22”/24”/26”). However, as a deviated large sized hole requires a very high flow rate to remove the cuttings, it is necessary to limit the maximum angle in the hole section, often in the range of 20-30 deg. Also, minimising the hole size will greatly improve hole cleaning, e.g. by drilling a 22” hole instead of 24” or 26” if possible. Drilling a pilot hole and then opening up to the full size only marginally reduces the required flow rate for effective hole cleaning.

4.1.10 Use of Larger Drillpipe
The pump pressure is often the limiting factor for achieving the required flow rate for hole cleaning. Therefore, it is often necessary to use larger than conventional 5” drillpipe such as 5½” or 6 5/8” in order to reduce the pump pressure. However, as use of a larger drillpipe size results in higher surface torque, its length should be optimised.
4.1.11 Circulation Prior to Connections or Tripping
Before making a connection, the hole should be circulated at the normal flow rate to clear the cuttings from around the BHA. Depending upon the hole angle and the length of BHA, a circulation time of 5 to 10 min is often necessary.

Before tripping out, the hole should be circulated at the normal flow rate until the shakers are clean, and the drillpipe be rotated at maximum speed/reciprocated in the mean time. This may require up to 3 bottoms-ups, depending upon the hole angle and hole size. Table 3 below lists typical calculated bottoms-ups required prior to tripping.

<table>
<thead>
<tr>
<th>Hole Angle</th>
<th>8½”</th>
<th>12¼”</th>
<th>17½”</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>130%</td>
<td>130%</td>
<td>150%</td>
</tr>
<tr>
<td>10 - 30</td>
<td>140%</td>
<td>140%</td>
<td>170%</td>
</tr>
<tr>
<td>30 - 60</td>
<td>160%</td>
<td>180%</td>
<td>250%</td>
</tr>
<tr>
<td>60 +</td>
<td>170%</td>
<td>200%</td>
<td>300%</td>
</tr>
</tbody>
</table>

4.1.12 Wiper Trips
Wiper trips or pumping-out-of-hole are often effective in eliminating hole cleaning problems, therefore, it is good practice to have regular wiper trips, say every 150 or 200 m back into the previous casing when drilling a high angle section. This is particularly important if the actual flow rate is below or close to the critical rate.

4.1.13 Data Acquisition
It is advised that trend sheets be used to log all hole cleaning parameters for future use, i.e. flow rate, rpm, mud rheology Vs depth and evidence of dirty hole on trips etc. Trip procedures should be prepared in advance with guidance on tripping intervals, backreaming rates and maximum overpull. These procedures can be modified over the well as necessary.

By measuring the amount of cuttings over the shakers at regular intervals a cuttings return log can be established which will provide valuable information on trends in cuttings returns versus ROP.

4.1.14 Hole Enlargement
In situations where out-of-gauge sections are common, every effort should be made to minimise the extent of hole enlargement. Factors such as mud design (chemical) and mud weight selection must be optimised to reduce the problem. Poorly consolidated formations can be prone to hydraulic and mechanical erosion. Bit hydraulics and drilling practices should be designed accordingly.

In highly active techtonic areas such as Colombia the wellbore sections due to nature of formations drilled are generally out of gauge. This causes a reduction in the annular velocity of the mud which together with the large cavings (and hence higher slip velocity), makes hole cleaning much more critical.