CHAPTER-5

HYDRAULICS

The hydraulic system serves many purposes in the well. Since it is centred on the mud system, the purposes of mud and hydraulics are often common to each other. The hydraulics system has many effects on the well. Therefore, the reasons for giving attentions to hydraulics are abundant. The more common reasons are as follows:

-Control sub-surface pressures,

-Provide a buoyancy effect to the drill string and casing,

-Minimize hole erosion due to the mud's washing action during movement,

-Remove cuttings from the well, clean the bit, and remove cuttings from below the bit,

-Increase penetration rate,

-Size surface equipment such as pumps,

-Control surge pressures created by lowering pipe into the well,

-Minimize well bore pressure reductions from swabbing when pulling pipe from the well,

-Evaluate pressure increases in the well bore when circulating the mud,

-Maintain control of the well during kicks,

Hydrostatic Pressure

The hydrostatic pressure of the drilling fluid is an essential feature in maintaining control of a well and preventing blow-outs. It is defined, in a practical sense, as the static pressure of a column of fluid. Although the fluid is generally mud, it can include air, natural gas, foam, mist, or aerated mud. Only liquid-based systems such as mud will be considered in this text. The hydrostatic pressure of a mud column is a function of the mud weight and the true vertical depth of the well. It is imperative that attention be given to the well depth so that the measured depth, or total depth, is not used inadvertently.

Since mud weights and well depths are often measured with different units, the equation constants will vary. Common forms of the hydrostatic pressure equation are as follows:

P_H = 0.052 (mud weight, lb/gal) (depth, ft), P_H = psia
P_H = 0.00695 (mud weight, lb/cu ft) (depth. ft), P_H = psia
P_H = 9.81 (mud weight, g/cm^3) (depth, m), P_H = kPa

If a column of fluid contains several mud weights, the total hydrostatic pressure is the sum of he individual sections:

$$P_H = \sum c\, \rho_i\, L_i$$

c = conversion constant
ρ = mud weight for the section of interest
L = length for the section of interest

Equivalent Mud Weight

Drilling operations often involve several fluid densities, pressures resulting from fluid circulation, and perhaps applied surface pressure during kick control operations. It is useful in practical applications to discuss this complex pressure and fluid density arrangement on a common basis. The approach most widely used is to convert all pressures to an "equivalent mud weight" that would provide the same pressures in a static system with no surface pressure.

Suppose a 10,000-ft well has two mud weights. It contains 5,000 ft of 9.0 lb/gal mud and 5,000 ft of 11.0-lb/gal mud. The equivalent mud weight at 10,000 ft is 10.0 lb/gal, even though the well does not contain any real 10.0 lb/gal mud. Another term commonly used to describe the **equivalent mud weight** concept is ***ECD***, or equivalent circulating density. The ECD usually considers the hydrostatic pressures and the friction pressure resulting from fluid movement. For example, a 12.0 lb/gal mud may act as if it is 12.3-lb/gal mud (due to the friction pressure) while it is pumped. Some drilling engineers may refer to the ECD in this case as 0.3 lb/gal. Typical ranges for the ECD additive factor are 0.1-0.5 lb/gal.

EMW = (total pressure x 19.23) / true vertical depth

EMW = equivalent mud weight, lb/gal

19.23 = reciprocal of the 0.052 constant

Example-1: An intermediate casing string (see the figure) will be cemented as shown. Calculate the hydrostatic pressure at 12,000 ft. Convert the pressure at 12,000 ft to an equivalent mud weight and determine if it will exceed the fracture gradient of 14.2 lb/gal.

Solution:

The hydrostatic pressures are computed as follows:

0.052 x fluid weight x depth = pressure

0.052 x 11.4 lb/gal x (7,000ft) = **4,149 psi**

0.052 x 15.4 lb/gal x (9,000 - 7,000ft) = **1,602 psi**

0.052 x 16.61b/gal x (12,000 - 9,000 ft) = **2,589 psi**

Total hydrostatic pressure = **8340 psi**

The equivalent mud weight is calculated as:

EMW = (total pressure x 19.23) / true vertical depth

EMW = (8340 x 19.23) / 12000 = 13.36 lb/gal (ppg)

Therefore, the static hydrostatic pressure with a 13.36-lb/gal EMW will not exceed the fracture gradient of **14.2 lb/gal.**

Buoyancy

The drilling fluid provides a beneficial effect relative to drill string weight or hook load. When pipe is lowered into the well, the mud system will support, or buoy, some of the pipe weight. This effect is termed buoyancy, or buoyant forces. The buoyed weight of the drill string will be less than the in-air weight of the pipe. Buoyant forces are a function of the volume and weight of the displaced fluid. Heavier mud has greater buoyant forces than low-density mud.

BW = BF x (in-air weight)

BW = buoyed weight

BF = buoyancy factor

BF = 1 – (ρ_m / 65.5)

ρ_m = mud density, lb/gal and 65.5 is the density of a gallon of steel.

Example-2: Casing string will be run into a well that contains 11.7 ppg mud. Assume the casing will be filled with mud as it is run. If the engineer uses a derrick safety factor of 2, will the 1,000,000 lb derrick capacity be satisfactory?

Casing weight, lb/ft	Section length, ft
47.0	4500
53.0	5500
47.0	3000

Solution:

1. The casing string weight, in air, is:

4500 ft x 47.0 lb/ft = 211500 lb

5500 ft x 53.0 lb/ft = 291500 lb

3000 ft x 47.0 lb/ft = 141000 lb

Total casing string weight in air is = 644000 lb.

BF = 1 – (ρ_m / 65.5)

BF = 1 – (11.7 / 65.5) = 0.82

Buoyed weight = 0.82 x 644000 lb = 528964 lb

Applying a derrick safety factor of 2.

2 x 528964 > 1000000 lb

Therefore, the derrick load will exceed the design criteria if a factor of 2 is used. He actual design factor is,

1000000 / 528964 = 1.89

Flow Regimes

While drilling fluids are flowing in a well, the manner in which the fluid behaves may vary. This behavior is often termed the flow regime. The most common regimes are **laminar, turbulent,** and **transitional**. Unfortunately, it is impossible to clearly define each type in the well. As an example, mud flow may be predominantly **laminar**, although the flow near the pipe walls during pipe rotation may be **turbulent.**

Laminar Flow

The most common annular flow regime is laminar. It exists from very low pump rates to the rate at which turbulence begins. Characteristics of laminar flow useful to the drilling engineer are low friction pressures and minimum hole erosion. Laminar flow can be described as individual layers, or laminae, moving through the pipe or annulus. The center layers usually move at rates greater than the layers near the well bore or pipe. The flow profile describes the variations in layer velocities. These variations are controlled by the shear-resistant capabilities of the mud. A high yield point for the mud tends to make the layers move at more uniform rates. Cuttings removal is often discussed as being more difficult with laminar now. The cuttings appear to move outward from the higher-velocity layers to the more acquiescent areas. These outer layers have very low velocities and may not be effective in removing the cuttings. A common procedure for minimizing the problem is to increase the yield point, which decreases layer velocity variations. An alternative is to pump a 10-20-bbl high-viscosity plug to "sweep" the annulus of cuttings.

Turbulent Flow

Turbulence occurs when increased velocities between the layers create shear strengths exceeding the ability of the mud to remain in laminar flow. The layered structure becomes chaotic and turbulent. Turbulence occurs commonly in the drill string and occasionally around the drill collars. Much published literature suggests that annular turbulent flow increases hole erosion problems. The flow stream is continuously swirling into the walls. In addition, the velocity at the walls is significantly greater than the wall layer in laminar flow. Many industry personnel believe that turbulent flow and the formation type are the controlling parameters for erosion.

Transitional Flow

Unfortunately, it is often difficult to estimate the flow rate at which turbulence will occur. In addition, turbulence may occur in various stages. It is convenient to describe this "grey" area as a transitional stage.

Turbulence Criteria

Several common methods can be used to establish turbulence criteria. The most common approach is the Reynolds number. Others include **1)** intersection of the flow rate vs. pressure loss calculations for laminar and turbulent flow and **2)** calculation of a z-value. The Reynolds number approach is used almost exclusively in the industry. Turbulence occurs when the ratio of the momentum of the liquid to the viscosity ability of the liquid to dampen permeations exceeds some empirically determined value. The momentum force of the liquid is its velocity times its density. The viscous ability of the liquid to damp out permeations is the internal resistance against change and the effects of the walls of the borehole. For the simple case of Newtonian, non elastic liquid flowing in a pipe dampening effect is the quotient of the viscosity and the diameter of the well bore.

$$NR = \rho\ V\ D\ /\ \mu$$

NR = Reynolds number
ρ = density
D = diameter
μ = viscosity

A simpler equation used in the literature to predict the Reynolds number at the upper limit of laminar flow is as follows:

$$\mathbf{N_R = 3{,}470 - 1{,}370\ n}$$

The relation for the Reynolds number between the transition and turbulent flow regimes is

$$\mathbf{N_R = 4{,}270 - 1{,}370\ n}$$

It is obvious from equations that the Reynolds number is sliding, with its dependency on the flow behavior index **(n)**. The position of intersection between the laminar and turbulent flow pressure losses depends on the equations being used. The Reed slide rule or the Hughes tables can give errors if the mud is quite non-Newtonian at the applicable shear rate.

Critical Velocity

The term critical velocity is used to define the single velocity at which the flow regime changes from laminar to turbulent. This variable is the most important since all other members are considered constant in a typical equation. Since no single Reynolds number defines the transitional zone, it follows that a range of critical velocities may be necessary to determine the flow regime.

In practical applications, a critical velocity ($\mathbf{V_c}$) and an actual velocity ($\mathbf{V_{al}}$) are calculated. If $\mathbf{V_{al} < V_c}$ the flow is **laminar**. If $\mathbf{V_{ic} < V_a}$ the flow is **turbulent**. If $\mathbf{V_{al} \cong V_c}$ calculations are made with both flow regimes and the larger pressure losses are used.

Flow (Mathematical) Models

A mathematical model is used to describe the fluid behavior under dynamic conditions. The model can be used to calculate friction pressures, **swab** and **surge** pressures, and slip velocities of cuttings in fluids. The models most used in the drilling industry are ***Newtonian, Bingham Plastic, and Power Law.***

Terms used in mud models are **shear stress** and **shear rate**. They can be described by considering two plates separated by a specified distance with a fluid. If a force is applied to the upper plate while the lower plate is stationary, a velocity will be reached and will be a function of the force, the distance between the plates, the area of exposure, and the fluid viscosity:

$$F / A = \mu (V / X)$$

F = force applied to the plate; *A* = contact area; *V* = plate velocity *X* = plate spacing μ = fluid viscosity

The quotient of **F/A** is termed the shear stress (τ), while **V/X** is shear rate (γ)

$$\tau = \mu \gamma$$

In drilling operations, the shear stress and shear rate are analogous to **pump pressure** and **rate**, respectively.

Newtonian Fluids

The model used initially to describe drilling mud was the Newtonian model,

$$\tau \; \alpha \; \gamma$$

It stated that pump pressure (shear stress) would increase proportionally to shear rate. If a constant of proportionality is applied to represent fluid viscosity,

$$\tau = \mu \gamma$$

Unfortunately, drilling mud usually cannot be described by a single viscosity term. They require two or more points for an accurate representation of behavior. As a result, the Newtonian model generally is not used in hydraulics plans.

Bingham Plastic

The Bingham model was developed to describe more effectively drilling mud presently in use. Bingham theorized that some amount of stress would be required to overcome the mud's gel structure before it would initiate movement

$$\tau = \mu_p \gamma + \tau_y$$

τ_y = yield stress,
μ_p = fluid viscosity

In practical terms, the equation states that a certain pressure would be applied to the mud to initiate movement. Flowing mud pressures would be a function of the initial yield pressure and the fluid viscosity.

Shear rates are normally taken at 300 and 600 rpm rates on the viscometer. The fluid viscosity (μ_p) and the yield stress (τ_y) are calculated as follows:

$$\mu_p = \theta_{600} - \theta_{300}$$

θ_{600} , θ_{300} = readings at 600 and 300 rpm, respectively.

$$\tau_y = \theta_{300} - \mu_p$$

The fluid viscosity is termed plastic viscosity (**PV**) due to the plastic nature of the fluid and is measured in centi-poise (**cp**). The size, shape, and concentration of particles affect the plastic viscosity in the mud system. As mud solids increase, the plastic viscosity increases. The plastic viscosity is a mud property that is not affected by most chemical thinners and can be controlled only by altering the state or number of solids.

The yield stresses τ_y, is given the name of yield point and is measured in lb/100 ft^2. It is a function of the inter-particle attraction of the solids in the mud. Chemical thinners, dispersants, and viscosifiers control the yield point.

Power Law

The Power Law model is a standard mathematical expression used to describe a non-linear curve. The equation for drilling fluids is ;

$$\tau = K (\gamma)^n$$

K = consistency index; n = flow behavior index

The flow behavior index is descriptive of the degree to which the fluid is non-Newtonian.

$n = 3.32 \log (\theta_{600} / \theta_{300})$

$K = \theta_{300} / 511^n$

Example-3: *Use the following data to compute PV, YP, n and K.*

$\theta_{600} = 64$, $\theta_{300} = 35$,

Solution:

$PV = \theta_{600} - \theta_{300} = 64 - 35 =$ **29 cp**

$YP = \theta_{300} - PV = 35 - 29 =$ **6 lb/100ft^2**

$n = 3.32 \log (\theta_{600} / \theta_{300})$

$n = 3.32 \log (64 / 35) =$ **0.87**

$K = \theta_{300} / 511^n$

$K = 35 / 511^{0.87} =$ **0.154**

Friction Pressure Determinations

Pumping a drilling fluid requires overcoming frictional drag forces from fluid layers and solids particles. The pump pressure (P_p) can be described as the summation of the frictional forces in the circulation system:

$P_p = P_{DS} + P_B + P_A$

P_p = pump pressure, psi;

P_{DS} = drill string friction pressure, psi;

P_B = bit pressure drop, psi;

P_A = annulus pressure, psi

The pressure drop in the bit results from fluid acceleration and not solely friction forces. As a result, it will be discussed in a separate section. Equations to determine friction pressures vary according to the flow regimes, such as laminar and turbulent. In addition, Bingham Plastic and Power Law models differ in form. Since these models are frequently used in drilling applications, they will be presented in the following sections. Newtonian-based equations will not be presented.

Bingham Plastic Friction Pressures

The Bingham Plastic model is used primarily to compute friction pressure associated with laminar flow. This restriction is based on its inability to accurately describe shear stresses associated with high shear rates. Laminar and turbulent flow calculations will be presented, however, since they are frequently used in the drilling industry.

The velocity of the fluid in the **drill string** is described as;

$$V = Q / (2.448\ d^2)$$

V *= fluid velocity, ft/sec;*

Q *= flow rate, gal/min;*

d *= pipe diameter, inch*

The critical velocity (V_c) for laminar and turbulence determination is computed;

$$V_c = [1.08\ PV + 1.08\ \sqrt{(PV)^2 + 12.34 d^2\ YP\ \rho}\ ] / \rho d$$

ρ = mud weight, ppg

Friction pressures for **laminar flow** can be calculated as follows:

$$P_p = [(PV\ L\ V) / 1500\ d^2)] + [(YP\ L) / 225\ d)]$$

L = section length, ft

Turbulent flow is calculated as;

$$P_p = (\rho^{0.75}\ V^{1.75}\ PV^{0.25}\ L) / 1800\ d^{1.25}$$

In the **annulus**, same series of operations is performed but slightly different equations to account for the hole geometry,

$$V = Q / [2.448\ (d_h^2 - d_p^2)]$$

d_h = casing or hole ID, inch ; d_p = pipe or drill collar OD, inch

$$V_c = [1.08 + 1.08\ \sqrt{(PV)^2 + 9.26(d_h - d_p)^2\ YP\ \rho}\ ] / \rho\ (d_h - d_p)$$

For laminar flow;

$$P_A = [(PV\ L\ V) / 1000\ (d_h - d_p)^2)] + [(YP\ L) / 200(\ d_h - d_p)]$$

For turbulent flow;

$$P_A = (\rho^{0.75}\ V^{1.75}\ PV^{0.25}\ L) / 1396\ (d_h - d_p)^{1.25}$$

Example-4: *Calculate friction pressures for flow rates of 100 and 200 gpm. Use the Bingham model.*

Pipe ID = 3.5 inch; MW = 12.9 ppg; PV = 29 cp;YP = 6 lb/100ft^2 ; Length = 10000 ft

Solution:

$V = Q / (2.448\ d^2)$

$V = 100 / [2.448\ (3.5)^2]$ = **3.33 ft/sec (at 100 gal/min)**

$V = 200 / [2.448\ (3.5)^2]$ = **6.66 ft/sec (at 200 gal/min)**

$V_c = [1.08\ PV + 1.08\ \sqrt{}(PV)^2 + 12.34 d^2\ YP\ \rho\ ] / \rho d$

$V_c = [1.08\ (29) + 1.08\ \sqrt{}(29)^2 + 12.34(3.5)^2\ (6)\ (12.9)\ ] / (12.9)\ (3.5)$ = **3.37 ft/sec**

For the flow rate of *100 gal/min,* the actual velocity (**V_a**) is slightly **less** than the critical velocity (**V_c**) of *3.37 ft/sec*. Use the laminar flow equation. (Note that the difference between V, and V, is small. Therefore, it might be advisable in some cases to consider calculating pressure losses for laminar and turbulent flow and use the larger value.)

$P_{DS} = [(PV\ L\ V) / 1500\ d^2)] + [(YP\ L) / 225\ d)]$

$P_{DS} = [(29)(10000)\ (3.33) / 1500\ (3.5)^2)] + [(6)\ (10000) / 225\ (3.5)]$ = **128.6 psi**

At a flow rate of *200 gal/min*, the actual velocity of *6.66 ft/sec* is significantly greater than the critical velocity of *3.37 ft/sec*. Therefore, use the turbulent flow equation;

$P_{DS} = (\rho^{0.75}\ V^{1.75}\ PV^{0.25}\ L) / 1800\ d^{1.25}$

$P_{DS} = (12.9)^{0.75}\ (6.66)^{1.75}\ (29)^{0.25}\ 10000) / 1800\ (3.5)^{1.25}$ = **505.7 psi**

The laminar and turbulence equations can be used to illustrate the basic difference between these two flow systems. In the laminar equations, a value for the yield point (YP) is a significant part of the pressure loss, particularly when it is observed that the PV value is divided by a squared diameter. The turbulent flow equations do not contain a YP term. The yield point is one of the forces creating the inter-particle attractions, causing the mud to move in laminae. When the shear force exceeds the yield stress, turbulence begins and the yield point is not a factor thereafter.

Power Law Friction Pressures

Power Law calculations follow the same sequence as the Bingham model. Actual and critical velocities are compared to determine the flow regime before calculating the pressure loss. If $\mathbf{V_a}$ and $\mathbf{V_c}$ differ significantly, choose the appropriate flow equation. When $\mathbf{V_a} \cong \mathbf{V_c}$ makes both pressure loss computations and chooses the larger.

A word of caution must be given at this point relative to Bingham and Power Law equations. Many forms of these computations exist in the industry with units that differ slightly. Velocity can be expressed in *ft/sec* or *ft/min,* which obviously would make a significant error in the calculations, particularly when V is in exponent form. The Power Law model demands additional attention because several methods exist for computing the basic parameters of *n* and *K.* This is not the case for the Bingham model because only one accepted method is used for PV and YP calculations. The equations presented in this text are those of Moore et al.

Calculating friction pressures in the drill string using the Power law equations for **laminar** and **turbulent** flow are accomplished respectively:

$P_{DS} = [(1.6V / D) ((3n + 1) / 4n)]^n (KL / 300d)$ **-laminar-**

$P_{DS} = [2.27 (10^{-7}) \rho^{0.8} V^{1.8} PV^{0.2} L] / d^{1.2}$ **-turbulent-**

For computation simplicity, N_R = 3000 is assumed for turbulence criteria. Basic assumptions for friction factor correlations result in the critical velocity equation:

$$\mathbf{V_c = [5.82\ (10^4)\ K\ /\ \rho]^{1/2-n}\ [(1.6/d)\ ((3n+1)\ /\ 4n)]^{n/2-n}}$$

Annular flow equations follow the same pattern as drill string calculations.

$$\mathbf{P_A = [(2.4V\ /\ (d_h - d_p))\ ((2n + 1)\ /\ 3n)]^n\ [(KL\ /\ 300\ (d_h - d_p)]}$$ **-laminar-**

$$\mathbf{P_{DS} = [7.7\ (10^{-5})\ \rho^{0.8}\ V^{1.8}\ PV^{0.2}\ L]\ /\ [(d_h - d_p)^2\ (d_h + d_p)^{1.8}]}$$ **-turbulent-**

$$\mathbf{V_c = [3.878\ (10^4)\ K\ /\ \rho]^{1/2-n}\ [(2.4/\ (d_h - d_p))\ ((2n+1)\ /\ 3n)]^{n/2-n}}$$

<u>Example-5:</u> Refer to previous example and compute the friction pressures for the system. Use the Power law model and flow rate of 125 gal/min. If $\mathbf{V_a \cong V_c}$, computes the pressure drop for laminar and turbulent flow and choose the larger value.

n = 0.87; *K* = 0.154; *Pipe ID* = 3.5 inch; *MW* = 12.9 ppg; *Length* = 10000 ft;*PV* = 29 cp;

<u>Solution:</u>

-Determine the actual velocity at 125 gal/min;

$V_a = [125\ /\ 2.448\ (3.5)^2]$ = **4.168 ft/sec (250 ft/min)**

-Compute critical velocity;

$$V_c = [5.82\ (10^4)\ K\ /\ \rho]^{1/2-n}\ [(1.6/d)\ ((3n+1)\ /\ 4n)]^{n/2-n}$$

$$V_c = [5.82\ (10^4)\ 0.154\ /\ 12.9]^{1/2-0.87}\ [(1.6/3.5)\ ((3(0.87)+1)\ /\ 4(0.87))]^{0.87/2-0.87}$$

V_c = **183 ft/min**

-For purpose of illustration in this example, assume $\mathbf{V_a \cong V_c}$ (**250 ft/min** ≅ **183 ft/min)**

-Calculate laminar flow pressure losses;

$$P_{DS} = [(1.6V\ /\ D)\ ((3n + 1)\ /\ 4n)]^n\ (KL\ /\ 300d)$$

$$P_{DS} = [(1.6 \times 250\ /\ 3.5)\ ((3(0.87) + 1)\ /\ 4(0.87))]^{0.87}\ ((0.154)\ (10000)\ /\ 300(3.5))$$

= 95.4 psi

-Calculate turbulent flow pressure losses;

$P_{DS} = [2.27 (10^{-7}) \rho^{0.8} V^{1.8} PV^{0.2} L] / d^{1.2}$

$P_{DS} = [2.27 (10^{-7}) 12.9^{0.8} 250^{1.8} 29^{0.2} 10000] / 3.5^{1.2} =$ **158.6 psi**

-Since 158.6 psi > 93.4 psi, assume the pressure loss is the greater value.

Optimization of Drilling Hydraulics

The objective of a drilling hydraulics program is to specify the operating conditions which will maximize the bottom hole cleaning effect and hence penetration rate; while effectively removing the drilled cuttings from the hole. A number of parameters have to be considered when designing the hydraulics program:

1. Mud pump Output Volume (and Volumetric Efficiency)

2. Mud pump Output in terms of Hydraulic Power

3. Pressure losses in:

-Surface connections

-Drill pipe (inside and outside)

-Drill collars (inside and outside)

-Bit Nozzles

4. Velocity of mud passing through the bit nozzles (Nozzle velocity, V_n)

5. Velocity of mud rising in the annulus (Annular Velocity, V_{ann})

Mud Pump Output Volume:

The output volume flow rate, Q, depends on:

-pump line size

-pump stroke length

-pump speed (strokes/min.)

-pump volumetric efficiency

Two types of mud pump are in general use:

a) The Double Acting Duplex Pump

Pump Output, $Q = 0.0068 \times L \times (2D^2 - d^2) \times SPM \times (Vol.\ Eff.\ /100)$ -gal/min-

b) The Single Acting Triplex Pump

Pump Output, $Q = 0.0102 \times L \times D^2 \times SPM \times (Vol.\ Eff.\ /100)$ -gal/min-

L = stroke length, inch

D = inside diameter of liner, inch

d = rod diameter, inch

SPM = stroke per minute

Pumping a known value of mud or slurry and noting the SPM can determine volumetric Efficiency of the mud pumps. For the duplex pump the volumetric efficiency will usually be in the region of 90 % or more. The triplex pump will usually have a volumetric efficiency greater than 95 %.

Hydraulic Power

The pump output in hydraulic power is generally assumed to equal 85 % of mechanical or electrical input power.

$HHP = (P_t \times Q) / 1714$

P_t = circulating pressure, psi
Q = pump output volume, gal/min.

$P_t = P_s + P_{bit}$
P_s = pressure losses in the system, psi
P_{bit} = pressure losses over the bit nozzles, psi

Total $HHP = HHP_{system} + HHP_{bit}$

Total $HHP = [(P_s \times Q) / 1714] + [(P_{bit} \times Q) / 1714]$ **or**,

$HHP_{bit} = HHP_{total} - HHP_{system}$

$HHP_{bit} = [(P_t \times Q) / 1714] - [(P_s \times Q) / 1714]$

$HHP_{bit} = Q / 1714\ (P_t - P_s)$

Pressure Losses in the System

The system consists of all items causing pressure losses **except** the bit nozzles.

a)Surface Connections: from pump to drill pipe. Pressure losses are minimized by large internal diameters.

b) Drill Pipe: large ID and internal plastic coating reduce pressure drop.

c)Drill Collars: Large ID reduces pressure loss, but also reduces the useful weight per unit length.

d) Annulus: Pressure losses depends on the ratio of the drill string outside diameter and the hole size. It is desirable to reduce the back pressure on the formations, but annular losses are usually small.

As the rate of volume pumped varies, pressure losses in the system change as follows:

$$P_{system} = c\ Q^n$$

Q = flow rate (gal/min)
n = a variable power (1.86)
c = a constant

Pressure Drop Across Bit Nozzles

As the rate of volume pumped (Q) varies, the pressure losses at the bit change as follows:

Bit Pressure Drop, $P_{bit} = (156 \times W \times Q^2) / (D_n^2 + D_n^2 + D_n^2)^2$ **–psi-**

D_n^2 = nozzle size number, 1/32 inch

Q = flow rate, gal/min and *W =* mud weight, ppg

The jet velocity in the nozzles, V_n, can be calculated from

Jet velocity, $V_n = (418.3 \times Q) / (D_n^2 + D_n^2 + D_n^2)$ **-ft/sec-**

Therefore it can be shown as;

$P_{bit} = \rho V_n^2 / 58.26$ **-psi-**

Annular Velocity

The minimum annular velocity required cleaning the hole. It is important to avoid solids build-up and increasing the hydrostatic head, which might cause mud losses to the formation.

Annular Velocity , $V_{ann} = (24.5 \times Q) / (D_2^2 + D_1^2)$

D_2 = ID of hole, inch and D_1 = OD of pipe, inch

Optimization

Two principle approaches are adopted to achieve efficient removal of cuttings below the bit and so the best penetration rate:

-To maximize hydraulic power expended at the bit; assuming that cuttings removal depends on the fluid energy dissipated.

-To maximize the hydraulic impact force; assuming that formation is best removed when the mud hits the bottom of the hole with the greatest force.

It is also important to be able to quickly obtain a value of system pressure loss in the event of a kick, as this can be used to calculate circulating pressures at various killing speeds.

System Pressure Loss, $\mathbf{P_s = c\ Q^n}$

-By knowing the value of "n", the proportion of the circulating pressure which will be lost in the drill string under optimum hydraulics conditions ($P_{s,opt}$) can be determined.

,a) For maximum Hydraulic Power at the Bit

$\mathbf{P_{s,opt} = [1 / (n + 1)]\ P_t}$

b) For maximum Impact Force

$\mathbf{P_{s,opt} = [2 / (2 + 1)]\ P_t}$

-By knowing the value of “c” the corresponding optimum circulation rate can be determined.

-Once the optimum circulation rate and pressure are known, bit nozzle sizes can be selected to obtain the correct P_{bit} **(** $P_{bit} = P_t - P_{s,opt}$**)**

Theoretically "n" and "c" can be calculated from two pressures observed at two different pump rates.

$$n = \log (P_{s1} / P_{s2}) / \log (Q_1 / Q_2)$$

$$c = P_{s1} / Q_1^n$$

Small inaccuracies in pressure readings and pump stroke counts can result in considerable errors in "n" and "c". It is known that,

$$P_s = c\, Q^n$$

$$\log P_s = \log c + n \log Q$$

which (on log-log paper) is represented by a straight line with slope "n".

"c" can be calculated by solving, $c = P_s / Q^n$ for any combination of P_s and Q.

Example-6: Before starting a trip out at 9460 ft, to change the bit (12 1/4 with 3 x 14 nozzles), the following readings were taken:

Pump Rate (spm)	Circulating pressure (psi)
160	3480
135	2640
110	1810
88	1230

Mud pumps: **two** single acting triplex pumps, with 6" liner, 10" stroke, 97.5% volumetric efficiency. The mud gradient in use is: 0.676 psi/ft.

1. Calculate P_s for each circulation rate (Q).

2. Plot P_s - Q on log - log paper and determine n and calculate c.

3. For max. Hydraulic horsepower at the bit, calculate $P_{s\ opt}$ and Q_{opt}. assuming the max. pump pressure to be used is 3250 psi.

4. Determine the size of the nozzles for the next bit, to obtain optimum hydraulics.

5. Calculate bit and total hydraulic horse power for the next bit run.

6. Calculate annular velocity around 5" drill pipe.

7. Calculate nozzle velocity.

Solution:

1. For a triplex pump

$Q = 0.0102 \times L \times D^2 \times SPM \times Vol. Eff.$

$Q_1 = 0.0102 \times 10 \times 6^2 \times 160 \times 0.975 =$ **573 gal/min**

$Q_2 = 0.0102 \times 10 \times 6^2 \times 135 \times 0.975 =$ **483 gal/min**

$Q_3 = 0.0102 \times 10 \times 6^2 \times 110 \times 0.975 =$ **394 gal/min**

$Q_4 = 0.0102 \times 10 \times 6^2 \times 88 \times 0.975 =$ **315 gal/min**

To obtain P_s it is necessary to calculate P_{bit} for each circulating rate, from

$P_{bit} = (3013 \times W \times Q^2) / (D_n^2 + D_n^2 + D_n^2)^2$ –psi- (valid when mud weight is in psi/ft)

$P_{bit,1} = (3013 \times 0.676 \times 573^2) / (14^2 + 14^2 + 14^2)^2 =$ **1928 psi**

$P_{bit,2} = (3013 \times 0.676 \times 483^2) / (14^2 + 14^2 + 14^2)^2 =$ **1552 psi**

$P_{bit,3} = (3013 \times 0.676 \times 394^2) / (14^2 + 14^2 + 14^2)^2 =$ **899 psi**

$P_{bit,4} = (3013 \times 0.676 \times 315^2) / (14^2 + 14^2 + 14^2)^2 =$ **647 psi**

And because, $\mathbf{P_s = P_t - P_b}$, it follows that,

$P_{s1} = 3480 - 1928 =$ **1552 psi**

$P_{s2} = 2640 - 1370 =$ **1270 psi**

$P_{s3} = 1810 - 911 =$ **899 psi**

$P_{s4} = 1230 - 583 =$ **647 psi**

2. On the graph these values of $\mathbf{P_s}$ are plotted against **Q.**

$P_s = c\, Q^n$

$\log P_s = \log c + n \log Q$

which is a straight line on log-log paper with slope equal to "n".

Measured from the graph; n=**1.50**

$\mathbf{P_s = c\, Q^n}$

$Q_3 =$ **394 gal/min** and $P_{s3} =$ **899 psi**

$C = P_{s3} / Q^n = 899 / 394^{1.5} =$ **0.115**

3. For maximum hydraulic pressure at the bit.

$P_{s,opt} = [1 / (n + 1)]\, P_t$

$P_{s,opt} = [1 / (105 + 1)]\, P_t$ = **$0.4\ P_t$**

As maximum pump pressure is given as 3250 psi,

$P_{s,opt} = 0.4 \times 3250$ = **1300 psi**

$Q_{opt} = (P_s / c)^{1/n} = (1300 / 0.115)^{1/1.5}$ = **504 gal/min**

4. $P_{bit} = P_t - P_s = 3250 - 1300$ = **1950 psi**

$P_{bit} = (3013 \times W \times Q^2) / (3 \times D_n^2)^2$

$(3 \times D_n^2)^2 = 3013 \times 0.676 \times 504^2 / 1950$

$(3 \times D_n^2)^2$ = **514**

$D_n^2 = 171$

D_n = **13**

5. *General horse power equation;*

HHP = (P x Q) / 1714

HHP = (3250 x 504) / 1714 = **955 hp**

Bit HHP = (1950 x 504) / 1714 = **573 hp**

6. $V_{an} = (24.5 \times Q) / (D^2 - d^2)$

$V_{an} = (24.5 \times 504) / (12.25^2 - 5^2)$ = **99 ft/sec**

7. $V_n = (418.3 \times Q) / (3 \times D_n^2)$

$V_n = (418.3 \times 504) / (3 \times 13^2)$ = **416 ft/sec**