MUD ENGINEERING

This chapter covers the following items

- Function of drilling mud
- Drilling mud
- Types of drilling mud
  - Water base mud
  - Oil base mud
  - Emulsion mud
- Fundamental properties of mud
- Mud calculations
- Mud contaminant
- Mud conditioning equipment

Function of drilling mud

Cool bit and its teeth

- Drilling action requires mechanical energy in form of weight on bit, rotation and hydraulic energy
- Large part of energy dissipated as heat
- Heat must be removed to allow drilling
- Mud helps remove heat
- Mud helps remove cutting between the teeth and prevent bit balling

Cool and lubricate drill string

- Rotating drill string generates heat
- Mud help dissipate heat from hole
- Mud absorbs heat by convection and release it by radiation
- Mud lubricate drill string and reduce friction

Control formation pressure

- For safe drilling, high formation pressures must be contained within the hole to prevent damage and injury
- This achieved by hydrostatic pressure of mud
- Mud pressure should be higher than formation pressure

- An overbalance of 100-200 psi is used
- Pressure overbalance id referred as chip hold down pressure (CHDP)
- Penetration rate decreases as CHDP increases
- For abnormal pressure CHDP becomes negative and kick will happen

Carry cutting to surface

- Cutting generated by the bit must be removed
- Drilling mud carries cutting form bottom to surface
- Carrying capacity depend on annular velocity, plastic viscosity and yield point of mud and slip velocity of generated cutting
- For power law fluid, slip velocity is:

$$Vs = \frac{175 D_p (\rho_p - \rho_m)^{0.667}}{\rho_m^{0.333} \mu_e^{0.333}} \; ft/\min$$

$$Vs = \frac{15.23 D_p (\rho_p - \rho_m)^{0.667}}{\rho_m^{0.333} \mu_e^{0.333}} \; m/s$$

D_p = Particle diameter, in or mm

ρ_p = Particle density, ppg, g/l

ρ_m = Mud density, ppg, g/l

μ_e = **E**ffective viscosity, cp

- Annular velocity V_r is the flow rate divided by the annular area
- Lift velocity $V = V_r - V_s$
- The mud also must suspend cutting when drilling stops

Stabilize the wellbore

- Good mud cake stabilize the hole
- Differential pressure between mud and formation keep hole stable
- Reduce drilling time also help keep hole stable

Help in evaluation and interpretation of well logs

- During logging mud fill the hole
- Logs used to detect hydrocarbon, measure porosity, formation pressure
- Mud should posses properties that help evaluate these properties

Drilling mud

- Fresh water gives a pressure gradient of 0.433 psi/ft
- Normal formation pressure gradient is 0.465 psi/ft
- Fresh water can not control formation pressure
- Solids are added to increase water density to control pressure

Types of drilling mud

Water base mud

- Consists of:
    - Liquid water, continuous phase
    - Reactive solids, for viscosity and yield point
    - Inert solids, for density
    - Chemical additives, to control properties

Reactive solids

- Clays are added to provide viscosity and yield strength
- Mechanism is very complex
- Internal structure of clay particles and electrostatic forces develop viscosity
- Two types of clay are available
- Bentonite clay, montmorillomite (smectite) group used with fresh water
- Attapulgite clay, salt gel (playgorskite) group of clay used in fresh and salt water

Nature of clay

- Defines as natural, earthy, fine-grained material that develop plasticity when wet
- Form from chemical weathering of igneous and metamorphic rocks
- Mainly form from volcanic ash

- Wyoming bentonite is the famous one
- Atoms from layers
- There are three atomic layers: tetrahedral layer, octahedral layer, and exchangeable layer
- Tetrahedra made up of flat honeycomb sheet made up of silicon atom surrounded by four oxygen
- Tetraherdra are liked to form sheet by sharing three of their oxygen atoms
- Octahedral layer are sheets composed of linked octahedral, each made up of an aluminium and magnesium atom surrounded by six oxygen
- They linked through oxygen making three octahedra
- Exchangeable layers of atoms or molecules bound loosely into the structure giving the clay its physical properties
- The nature of these layers are stacked together on top of one another define the type of clay
- The sandwiches of tetrahedral and octahedral layers are joined with exchangeable layer
- Distance between layers are 9-15 Angstrom units (0.9-1.5 mm)
- In some clays, the exchangeable layer is relatively tightly bound in the structure
- Cation exchange capacity (CEC) measures how readily exchange take place
- CEC measured by dispersing a known amount of clay in a solution of magnesium chloride to replace as much as possible the exchangeable layer with magnesium
- It then transferred to a solution of potassium or calcium chloride
- The amount of potassium or calcium absorbed by clay is measured
- The amount is expressed in milliequivalents per 100 gm of dry clay and called (CEC)
- Typical values of bentonite are 70-130 and for attapulgite 5-99
- CEC used as a guide to the quality of clay

<u>Hydration of clay</u>

- Clays with high CEC exchange large amount of water into the exchangeable layer and adsorb water onto the outer surface of plates
- This effect gives high viscosity and high yield point

- Adsorption of water causes a very sticking expansion of clay
- For sodium bentonite, the distance between layers increased from 9.8 to 40 Angstrom
- For calcium bentonite from 12.1 to 17 A
- Overall hydration transform clay from dry power to plastic slurry
- The effectiveness is measured by yield of clay
- Yield of clay is defined as the number of barrels of 15 CP mud obtained from 1 ton (2000 lb) of dry clay
- Clay yield depends on: purity, nature of atoms in exchangeable layers and salinity of water

Bentonite or attapulgite

- Bentonite consists primarily of montmorillonite
- Came from French town Montmorillon, where first mined 1874
- Basic structure is close to pyrophllite.
- There are a small number of exchangeable ions, sodium calcium and magnesium
- Most common bentonite are those with sodium and calcium as exchangeable ions
- Attapulgite belongs to a different family of clay minerals
- Instead crystallizing as platy crystals, it forms needle like crystals
- Have excellent viscosity and yield strength when mixed with salt water
- Disadvantage is suffering high water loss and poor sealing properties
- Dispersion, flocculation and deflocculation
- Agitating of clay suspension in water gives three modes: edge to edge; face to edge; and face to face
- Dispersion occurs with no face or edge association
- It results in increase in viscosity and gel strength
- Aggregate occurs with face to face association
- Aggregate results in a decrease in viscosity and gel strength
- Flocculation occurs with face to edge association
- It causes excessive gelation
- Flocculation can be broken by chemical thinners
- The resulting suspension is called deflocculated

Inert solids

- Include low gravity and high gravity
- Low gravity include sand and chert
- High gravity are added to increase mud weight or density
- Referred to as weighting materials
- Mud named as weighted mud, they are:

Barite (barium sulphate, $BaSO_4$) sp.gr. 4.2

- Used to prepare mud in excess of 10 ppg
- Referred to as weighting agent for low cost and high purity

Lead sulphides (galena) sp.gr. 6.5-7.0

- Allowing mud weight up to 35 ppg

Iron ores, sp. gr. 5+

- More erosive
- Contain toxic materials

Chemical Additives

- Used to control mud properties
- Divided into thinners and thickeners

Mud thinners

- Reduce viscosity by breaking attachment of plate through edge or face by attaching the clay plates

- **Phosphates:** sodium tertaphosphates ($Na_4P_3O_7$) and sodium acid pyrophosphated ($Ba_2H_2P_3O_7$), Suitable for any pH value, Limited to 175 F (70 C)

- **Chrome lignosulphonate**: Decomposes at 300 F (149 C), deflocculate and disperses clay, Reduce viscosity, yield strength and water loss, chrome lignosulphonate attaches to broken edges of clay reduces the attractive forces,

- **Lignite:** Decompose at 350 F (177 C), can be used as water loss agent

- **Surfactants** (surface tension reducing agent): Reduce water loss, Used as emulsifiers in oil base mud

Mud thickeners

- **Lime or cement:** Increase viscosity by flocculation resulting from replacement of Na^{+} cations by Ca^{++} cations

- **Polymers :**
- Large molecules made up of many repeated small units called monomers
- Used for filtration control, viscosity modification, flocculation and shale stabilization
- Cause little change in solid contents of mud
- Polymer mud have high shear-thinning ability at high shear rate
- This reduces viscosity and in turn frictional pressure loss
- Hydraulic bit horse power increases and in turn penetration rates
- Three types are available:

  - **Extenders:** sodium polyacrylate, increases viscosity by flocculating bentonite

  - **Colloidal polymer:** CMC, HEC and starch
    - **CMC:** an ionic polymer produced by treating cellulose with caustic soda and monochloro acetate, molecular weight ranges between 50,000 and 400,000

    - **HEC:** similar to CMC but hydrate in all types of salt waters

    - **Starch:** produced from corn or potatoes, molecular weight up to 100,000, used to develop viscosity and act as filtration control agent
    - Control filtration by forming sponge like bags wedges into the opening of the filter cake, disadvantage is that it is amenable to bacterial attack at low pH

- **Large chain polymer:** include xanthenes gum
  - It is water soluble
  - Produced by the action of bacteria on carbohydrates

- Molecular weight 5,000,000
- Amenable of bacterial attack at temperature above 300 F
- Build viscosity in all types of water
- More expensive
- Limited with 13 ppg mud

Types of water base mud

Clear water

- Fresh or saturated brine water can be used to drill hard, compacted and near-normally pressured formation

Native mud

- Water pumped down letting it react with formation containing clay or shale
- Water dissolves clay and return to surface as mud
- Characterize by high solid content and high filter loss resulting in thick filter cake

Calcium mud

- Reduce clay and shale swelling
- Superior to fresh water mud for drilling gypsum and anhydrite
- Compared to sodium, calcium cations strongly attaches to clay sheets
- The sheets tend to be pulled together and aggregated
- Calcium reduces clay swelling by 50% with 150 ppm concentration, therefore clay cuttings will be reduced
- Can tolerate high concentration of drilled solids with viscosity increase
- Two types are available: Lime mud and gyp mud

- **Lime mud:** up to 120 ppm soluble calcium
  - Prepared by mixing bentonite, lime ($Ca(OH)_2$), thinner, caustic soda and an organic filtration control agent
  - Lime provide the inhibiting ion (Ca^{++})

- **Gyp mud:** up to 1200 ppm soluble calcium
  - Similar to lime except that lime is replaced by gyp
  - Has greater stability than lime

Lignosulphonate mud

- Suitable for high density, > 14 ppg
- Work under high temperature 250-300 F (121-149 C)
- High tolerance for contamination of drilled solids, salt anhydrite, cement
- Low filter loss
- Consists of: Fresh or sea water, bentonite, chrome or ferrochrome lignosulphonate, caustic soda CMC or stabilized starch
- Optional materials such as lignite, oil, lubricants, surfactants
- Suitable for drilling shale
- Disadvantage; cause damage to reservoir permeability
- Now seldom used

KCl/Polymer muds

- Consists of: fresh or sea water; KCl; inhibiting polymer; viscosity building polymer (xanthenes); CMC or stabilized starch; caustic soda or caustic potash, and lubricants
- Suitable for drilling shale because it prevents shale sloughing
- Used to drill pay zone due to its low solid contents
- Known as low solid or nondisperssed mud
- Low tolerance to solids; need efficient desanders and desilters
- Have many advantages:
    - High shear thinning allow solids removal
    - High true yield strength
    - Improve bore hole stability
    - Good bit hydraulics
- Disadvantage is instability at temperature above 250 F (121 C)

Salt-saturated mud

- Water is saturated with sodium chloride; 315,000 ppm
- Drills salt domes and salt sections, prevent hole washout
- Used with polymer to inhibit the swelling of bentonitic shale
- Consists of: fresh, brine or sea water; common salt; encapsulating polymer, and CMC or starch
- Low tolerance to solids
- Need high filter loss additives

Oil base mud

- Water in oil emulsion
- Diesel or crude oil forms its continuous phase
- Sometimes called invert emulsion
- Water droplets are emulsified in oil
- Water is used for gel strength and barite content
- Soaps are used as emulsifiers
- Soups are made from monovalent ion (Na^{+}) or divalent ion (Ca^{++})
- The soap molecule bridge together oil and water interfaces
- Agitation is required to break the water into small droplets
- Oil/water ratio determine the final properties
- Higher oil water increases resistance to contamination and temperature stability
- Used to drill hole with severe stability
- More stable at high temperature
- An excellent to drill pay zone; reduce formation damage and preserve original permeability
- Disadvantages:
  - Contaminate the environment
  - Flammability hazards
  - Difficult removal of drilled solids due to high plastic PV
  - Difficult electric logging

Emulsion mud

- Water is a continuous (normal oil 5-10% by volume)
- Formulated by using sodium soap as emulsifier
- Oil is added to increase penetration rate, reduce filter loss, improve lubricity, reduce lost circulation and reduce torque and drag in directional well

Properties of mud

- Include weigh or density, rheological properties, filtrate and mud cake, and pH value

Mud weight or density

- Weight or mass per unit volume
- Depend on solids in the liquid, either in solution of suspended

- Calculated by sum of weighs over sum of volumes
- Increases by adding solid materials
- Decreased by adding water or oil or aerating the liquid
- Measured by mud balance: a steel cup filled with freshly mud sample and balanced on a knife edge
- Expressed in ppg, pcf or kg/m^3

Rheological properties

- They are plastic viscosity, yield point and gel strength

Plastic Viscosity (PV)

- Control the magnitude of shear stress develops as one layer of fluid slides over another
- Measure of friction between layers
- Provides a scale of the fluid thickness
- Decreases with increasing temperature; with liquids; the reverse with gasses
- Effective viscosity depends on fluid velocity flow pattern, difficult to measure, but calculated
- For Bingham plastic
- $$\mu_e = PV + \frac{300}{V_a}\left(D_h - D_p\right)YP$$
- For power law
- $$\mu_e = \left[\frac{2.4V_a}{(D_h - D_p}\frac{(2n+1)}{3n}\right]^n 200K\left(\frac{D_h - D_p}{V_a}\right)$$
- Plastic viscosity and yield point are measured by Viscometer
- Six readings are available at six rpm (3, 6, 100, 200, 300, 600)
- PV is the difference between reading sat 600 and that at 300
- YP is the difference between readings at 300 and PV
- March funnel is used to viscosity
- Measurement shows thickness or thinning of fluid
- Mud with poured in 1500 cc funnel with orifice at the end
- Time to collect 946 cc (one quart) is measured
- Time for water about 26 sec
- Time for the rest indicate the gel strength

Yield point

- A measure of the attractive forces between particles due to positive and negative charges
- Measure the forces causes mud to gel in case of motionless
- Shows a minimum level of stress must be provided before mud flow
- Expressed in $lb/100ft^2$

Gel strength

- Ability of mud to develop gel structure
- Defines the ability of mud to held solids and measure thixotropy
- Determined using viscometer
- The sample stirred at high speed and the allowed to rest for 10 sec or 10 min
- The torque readings at 3 rpm is taken as gel strength at specified time
- Expressed in $lb/100\ ft^2$
- Converted to metric by multiplying by 0.478

Filtration and filter cake

- Fluid loss against porous and permeable rock is called filter loss
- A layer of solids deposited on the rock is described as filter cake
- Loss occur when mud pressure is higher than formation pressure
- Quantity of mud loss depends on volume of filtrate and thickness and strength of filter cake, and differential pressure
- Can be determined by filter press, called API filter press
- Consists of a cylinder with 3 in diameter and 2,5 in length with fine screen at the base
- Pressure applied on the sample, 100 05 500 psi and 60 F
- HPHT filter press measure at bottom hole pressure and temperature
- The volume collected in cc per 30 min, API filter loss
- The thickness of mud cake in 1/32 in express the mud cake thickness
- Betonite, emulsified oil, dispersant, CMC and starch used to reduce filter loss, starch is used with pH > 11.5
- Ideal mud gives small filter loss and thin and tough mud cake

pH of mud

- Describe the acidity or alkalinity of mud

- Defined as the negative logarithm of the hydrogen ion (H^+)
- Measured by pH meter or strips
- The following table shows the pH value and the description of the fluid

H^+	OH^-	pH=-log H^-	Description
10^0	10^{-14}	0	Acidic
10^{-7}	10^{-7}	7	Neutral
10^{-10}	10^{-4}	10	Basic
10^{-17}	10^0	14	Basic

The following table shows the pH value of some solutions

Solution	pH
Distilled water	7
Bentonite suspension	8
Caustic soda, 10% concentration	
Lignite, 10%	5
Sodium acid phosphate	3.09-4.2

- Play a major role in controlling calcium stability
- Starch is used to increase pH to 11.5, but with bactericide
- Optimum pH between 8 and 11
- Minimum value of 7 should be maintained to control corrosion

<u>Mud calculations</u>

<u>Mud weight increase</u>

- Amount of barite
- $M = 1491 \frac{(\rho_{m1} - \rho_{m2})}{(35.5 - \rho_{m2})}$ Lbs
- Number of sacks

- $$S = 15.9 \frac{(\rho_{m2} - \rho_{m1})}{(35.5 - \rho_{m2})}$$ **Sacks**

- Mud volume increase due to adding barite

- $$V = \frac{42(\rho_{m2} - \rho_{m1})}{(35.5 - \rho_{m2})}$$ **Bbl**

To reduce mud weight by adding oil or water

- $$V_{o,w} = V_{m1} \frac{(\rho_{m2} - \rho_{m1})}{(\rho_{o,w} - \rho_{m2})}$$

Final mud density

- $$\rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$$
- Or

- $$\rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$$

In metric system

Mud weight increase

- Amount of barite

- $$M = 42500 \frac{(\rho_{m1} - \rho_{m2})}{(4250 - \rho_{m2})}$$ **Kg**

- Number of sacks

- $S = 996.7 \frac{(\rho_{m2} - \rho_{m1})}{(4250 - \rho_{m2})}$ **Sacks**

- Mud volume increase due to adding barite

- $V = \frac{10(\rho_{m2} - \rho_{m1})}{(4250 - \rho_{m2})}$ **m^3**

<u>To reduce mud weight by adding oil or water</u>

- $V_{o,w} = V_{m1} \frac{(\rho_{m2} - \rho_{m1})}{(\rho_{o,w} - \rho_{m2})}$

<u>Final mud density</u>

- $\rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$

- Or

- $\rho_{m3} = \rho_{m1} - \left(\frac{V_{m2}}{(V_{m1} + V_{m2})} \right) (\rho_{m1} - \rho_{m2})$

<u>Mud contaminants</u>

<u>Sodium chloride</u>

- Enters mud during drilling salt domes, rock salt beds, evaporites or any bed containing salt water
- Increase viscosity, yield strength and gel strength of bentonite mud due to flocculation
- Salt decreases pH value
- Salt solution cause hole enlargement, so salt saturated mud is recommended

- Routine measurements of mud chloride content are used to monitor the change in mud salinity
- Sudden increases indicates salt water flow

Anhydrite and gypsum

- Forms of calcium sulphate ($CaSO_4$)
- Formation containing anhydrite and gypsum are common in massive or interbedded
- Contamination leads to clay flocculation, increase viscosity, yield strength, filtrate loss and gel strength
- Caustic soda and chrome lignosulphonate are added to mud to drill these formation
- Sodium carbonate (Na_2CO_3) can added to treat mud

Cement

- Enter mud from poor cement jobs or squeeze cementing
- Increase viscosity, yield point and gel strength
- Discard mud used to drill cement
- Mud contaminated with cement treated with sodium bicarbonate
- Calcium content should be below 200 ppm

Mud conditioning

- Mud prepared by mixing water or oil with bentonite or attapulgite, barite and various chemicals
- Mud carries drilled cuttings to surface
- Mud loose much of its desired properties if drilled solids are not removed, and cause potential problems such as lost of circulation
- Mud conditioning equipment remove unwanted solids
- Three sections are available
    - Suction tank
    - Addition and mixing section
    - Removal section

The addition and mixing section

- Mixing operation involves pouring of mud solids or chemicals through a hopper connected to high shear jet
- The shear jet homogenize the mixture
- The resulting mud is again agitated with mud gun or an agitator

- The resulting mud is then directed to the suction tank
- The mud in the suction tank is handled with a centrifugal or charge pumps
- The charge pumps give the mud a pressure of 89 to 90 psi (5.5-6.2 bar) before it delivers to the main rig pump
- This improve the rig pump efficiency
- From the rig pump the mud flows through the circulation system

The removal section

- Consists of:
  - Shale shaker
  - Hydrocyclone
  - Mud cleaner
  - Centrifuge

Shale shaker

- A vibrating or rotating sieve
- Sieves have opening enough to pass mud and its solids
- Cuttings retained on the sieve and collected in a pit
- Can be single- or double-decker shaker
- Mud from shale shaker pass to sand trap below shale shaker
- Small drill cutting removed by gravity

Desander and desilter

- Mud from sand trap sent to desander and desilter (hydrocyclone)
- Centrifugal force separate solids from mud
- Hydrocyclones contain no moving parts
- Consists of:
  - An upper cylindrical section with a tangential feed tube and fitted with a vortex
  - A conical section ending with an apex
- Solids flow through the apex and discharged
- Clean mud flows through the vortex and send to the active pit
- Large size used for sandy particles (above 74 micron)
- Small-sized used for silty particles (2-74 micron)
- Desander diameter is from 6-12 in optimum 10 in
- Desilter diameter is from 4-5 in., not used with weighted mud

Mud cleaner

- Replaces desander and desilter for weighted mud
- Used to save barite
- Consists of a hydrocyclone with4 in diameter above a high-energy vibrating screen with openings of 10-125 micron
- The barite will pass through the screen and reused
- Advantage is to save barite, KCl, oil and mud
- Waste is much drier and need fewer disposal problems

Centrifuges

- Use centrifugal forces
- Separate heavy solids from liquid and lighter component
- Consists of:
  - Horizontal conical steel bowel, rotating at high speed
  - Double screw type conveyor inside the bowel rotated at low speed
  - The conveyor contains a hollow spindle for feeding mud
- The solids removed from the liquid by centrifugal forces
- The rotation of the bowel holds the slurry in bond against the wall of the bowel
- The conveyor blades scrapes or pushes the settled solids towards a narrow end of the bowel
- The solids collected are a dump particles with no fluids
- The liquid and clay particles collected as an overflow from ports at the large end of the bowel
- Clean mud requires treatment if properties changed

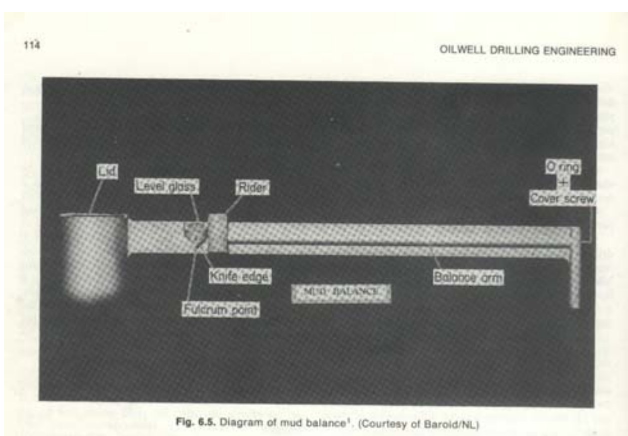
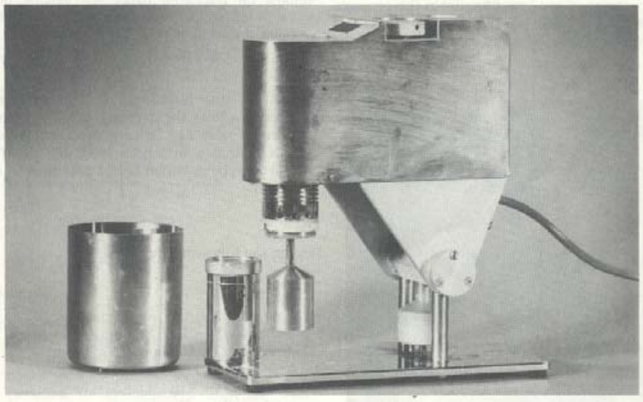
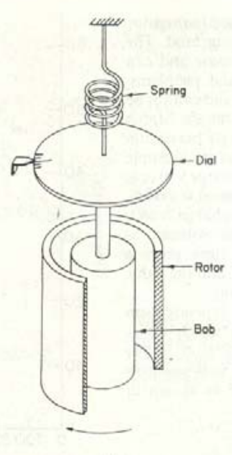


Fig. 6.5. Diagram of mud balance[1]. (Courtesy of Baroid/NL)



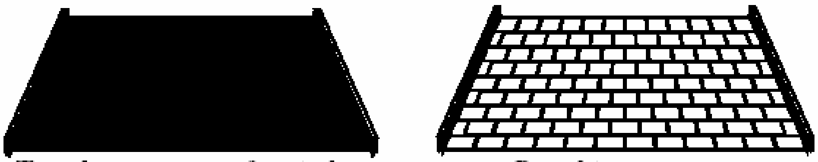
(b)

Fig. 6.6. (a) Diagram of concentric cylinder viscometer[7]; (b) apparatus for measuring viscosity, yield point and gel strength (rheometer). (Courtesy of API)[6]

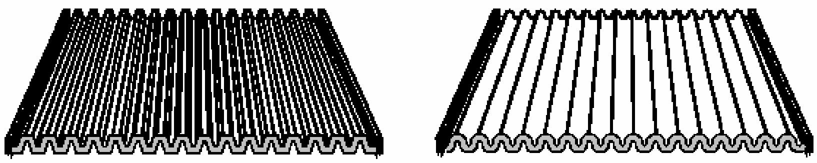


(a)

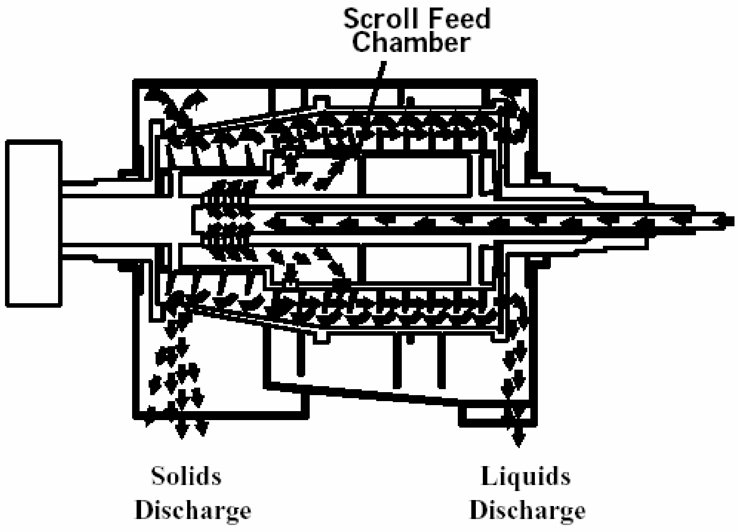
Two-dimensional

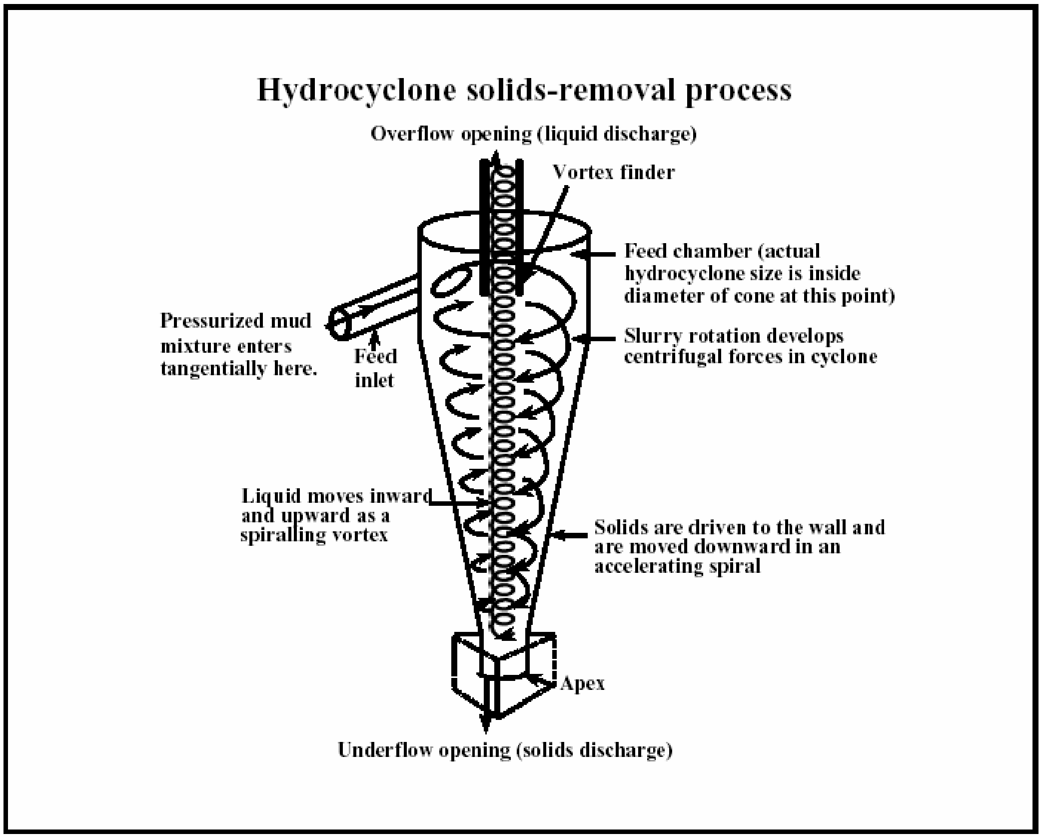


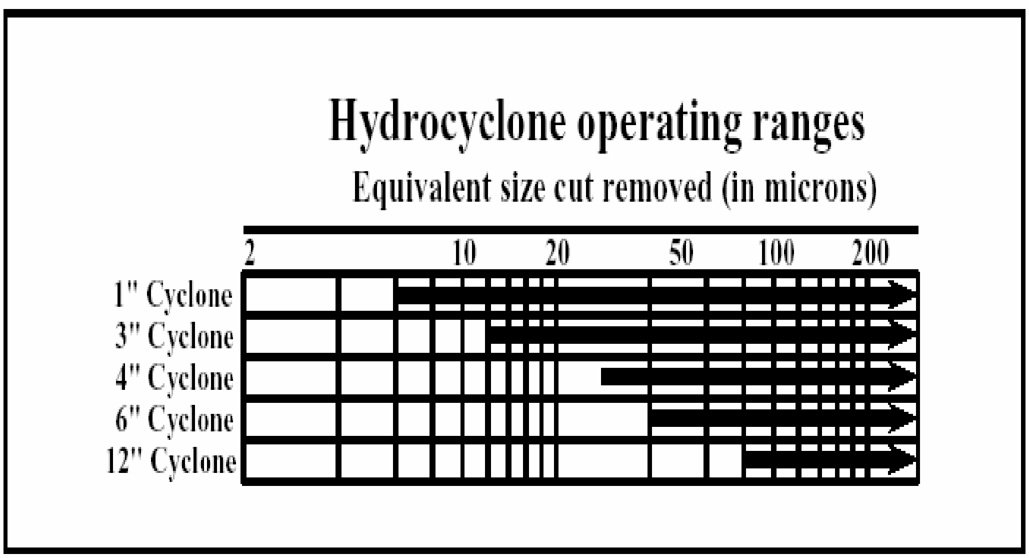
Three-dimensional



Decanting centrifuge cross-section




Hydrocyclone solids-removal process
Overflow opening (liquid discharge)
Vortex finder
Feed chamber (actual hydrocyclone size is inside diameter of cone at this point)
Pressurized mud mixture enters tangentially here.
Feed inlet
Slurry rotation develops centrifugal forces in cyclone
Liquid moves inward and upward as a spiralling vortex
Solids are driven to the wall and are moved downward in an accelerating spiral
Apex
Underflow opening (solids discharge)


Hydrocyclone operating ranges
Equivalent size cut removed (in microns)
2
10
20
50
100
200
1" Cyclone
3" Cyclone
4" Cyclone
6" Cyclone
12" Cyclone