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# Petroleum Extraction Engineering

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## Abstract

In this chapter, the information about rotary drilling rig components, their purpose and principles of operation is presented through the in-depth analysis of hoisting, rotating and circulating equipment. Detailed classification of drilling fluids and its content is followed by the thorough investigation of the phenomenon of drilling fluid losses. The effects of drilling mud additives and loss circulation materials on rheology and the rate of penetration of drilling mud are supported by the studies of comparing the rate of penetration of drilling mud with various loss circulation materials. Finally, the fluid capability to form filter cake on the borehole walls is presented through the physical simulation of flow.

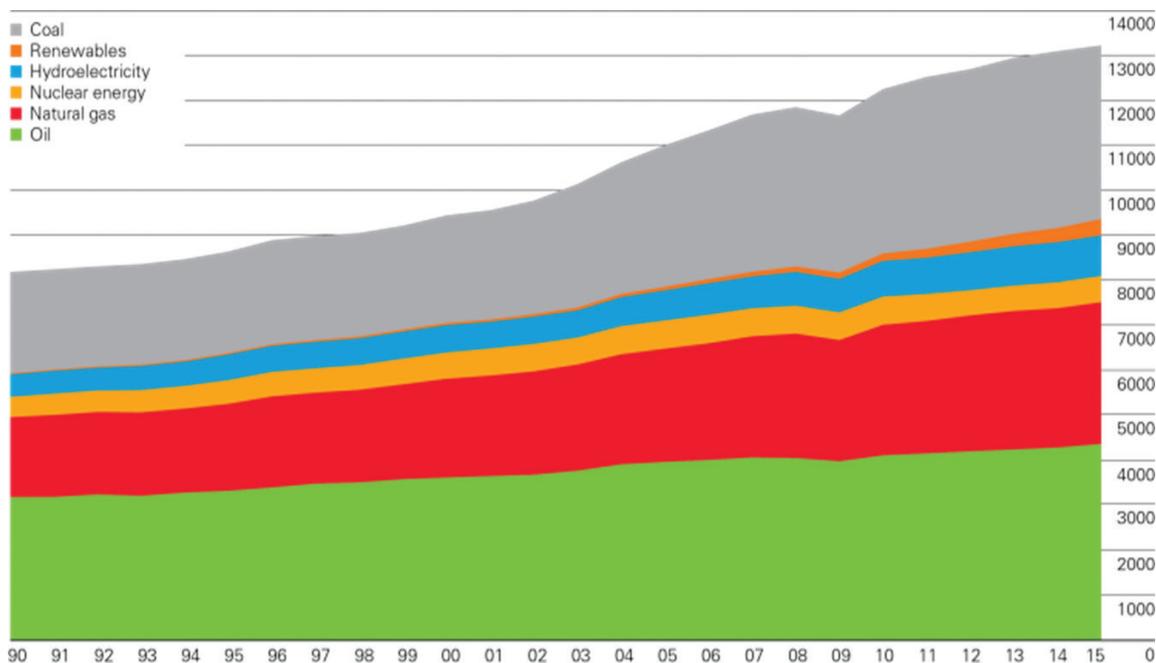
**Keywords:** petroleum extraction, oil well drilling, drilling fluid, drilling mud loss, filter cake

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## 1. Introduction

For more than a century, oil is well known as a good primary energy source competing coal, natural gas, nuclear energy and renewables in various regions and fields of the energy sector. According to the last statistical reports, oil is dominant fuel in America and Africa, whereas natural gas dominates in Europe and Eurasia and coal in the Asia Pacific. The use of oil and gas in the Middle East reach 98% of total energy consumption in this region.

Oil is the world's leading fuel (accounting for 32.9% of global energy consumption) with the 10-year average rate of growth of 1.9%. However, the rate of growth recorded in 2015 (1.0%) is slightly lower and similar to the rate recorded in 2014 (+1.1%) (**Figure 1**) [1].



**Figure 1.** Primary world energy consumption, million tonnes of oil equivalent [1].

Oil, originated from ancient fossilized organic materials, is considered as nonrenewable primary energy source with limited amounts. There are two indicators used to represent remaining oil reserves—proved oil reserves and reserves-to-production ratio. Proved oil reserves is amount of oil that geological information indicates with reasonable certainty can be recovered to the future under existing economic and operating conditions, whereas reserves-to-production ratio represents the length of time that those remaining reserves would last if production were to continue at the previous year's rate [1].

Constant growth of proved oil reserves from 1126.2 thousand million barrels in 1995 until 1697.6 thousand million barrels in 2015 is presented in **Figure 2**. Nearly half of proven oil reserves are located in the Middle East.

According to the last statistical overview, oil reserves increased by 24% over the past decade and meet 50.7 years of global production. On a regional basis, South and Central American reserves have the highest oil reserves-to-production ratios—117 years and Asia Pacific have the lowest reserves-to-production ratios—14.05 years.

In various regions all over the world, oil is found in the geological structures that form oil reservoirs. According to the depth of the oil reservoir, they are classified as follows: shallow, 30–800 m; medium, 800–2000 m; deep, 2000–5000 m and over deep, more than 5000 m. This classification is constantly changing as advances in drilling equipment with opportunity to achieve greater depth. However, irrespective of the depth of the oil reservoir, the main principle of oil extraction stays the same and is based on the life cycle of the oil field (**Figure 3**).

There are five stages of oil and gas fields' life cycle: exploration, appraisal, development, production and abandonment.

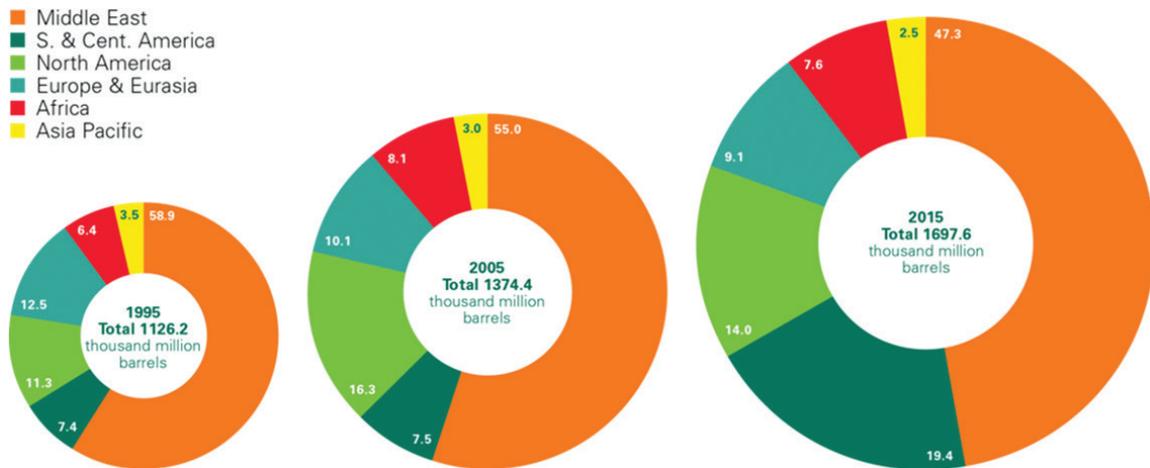


Figure 2. Distribution of proved oil reserves: 1995, 2005 and 2015, percentage [1].

**Exploration** is a method used for searching potentially viable oil and gas sources through geological surveys and drilling exploration wells to identify areas of potential interest. During the drilling process, general information and samples are collected to know about the rocks, fluids to find out how much oil and gas may be available at the explored area and what is the depth of the oil and gas window.

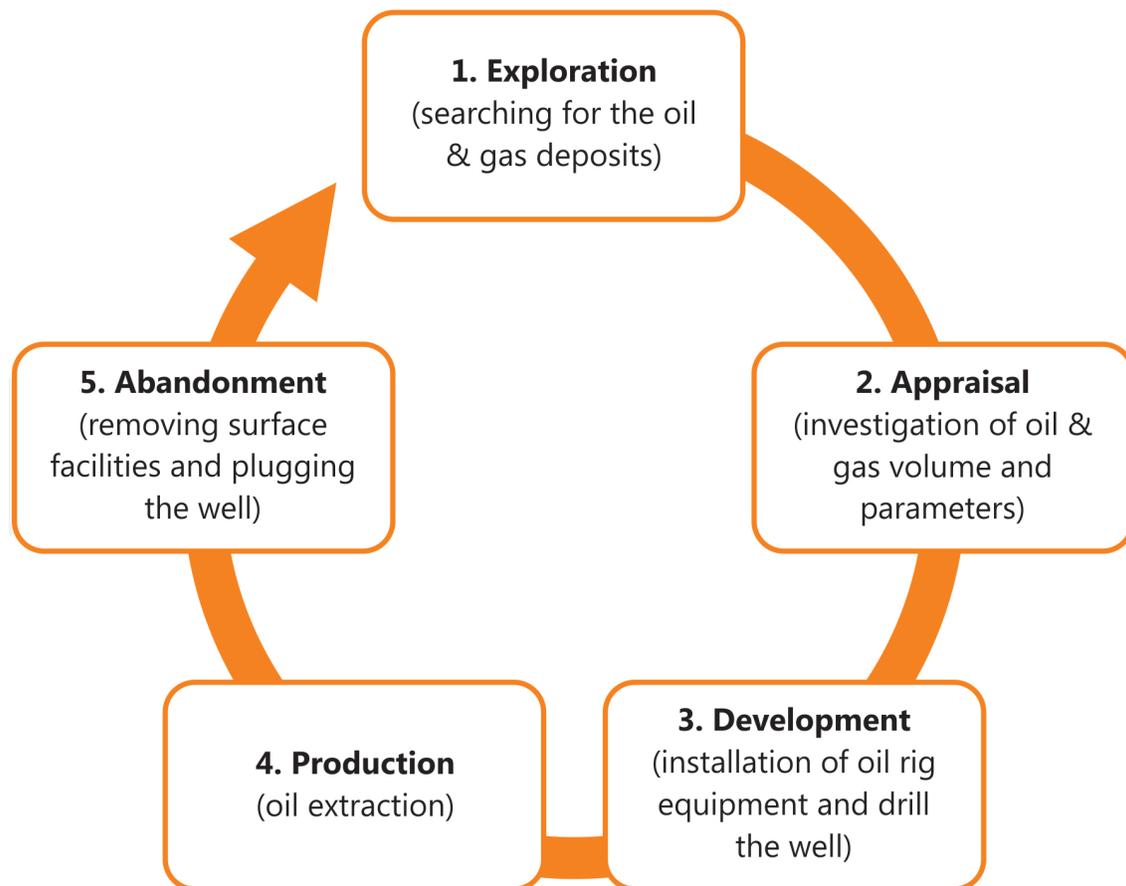


Figure 3. Life cycle of the oil and gas field.

After successful drilling exploration wells, the **appraisal** stage of the lifecycle starts. The main purpose of this phase is to improve the field description through further data acquisition and to reduce the uncertainty or possibility of losses about the size, shape and marketability of the oil and gas reservoir.

The **development** stage occurs after successful appraisal and before production. The main activities are formation of a conceptual development plan (in order to develop the oil and gas field, to prepare design for the production wells, to decide what surface and subsurface facilities are required and to describe operating and maintenance principles) and construction of the facilities and production units.

The **production** phase starts with the first oil flow in the wellhead. Oil and gas fields have a lifespan ranging from 15 to 30 years (from first oil to abandonment) and may be extended up to 50 years or more for the largest deposits. After extraction, oil and gas transported for processing and distribution.

When the oil and gas production is no longer cost-effective, wells are plugged and **abandoned**, production facilities are removed and this is the last stage of oil and gas fields' life cycle.

Thereinafter, we will be focusing on the third step of the life cycle of the oil field—development of the well.

## 2. Rotary drilling rig components

During the first phase of the development of the well, a rotary drilling rig is installed to bore a hole in the ground and reach the oil reservoir. The main rotary drilling rig components are derrick or mast, power and prime movers, hoisting equipment, rotating component, circulating system, tubular and tubular handling equipment and bit.

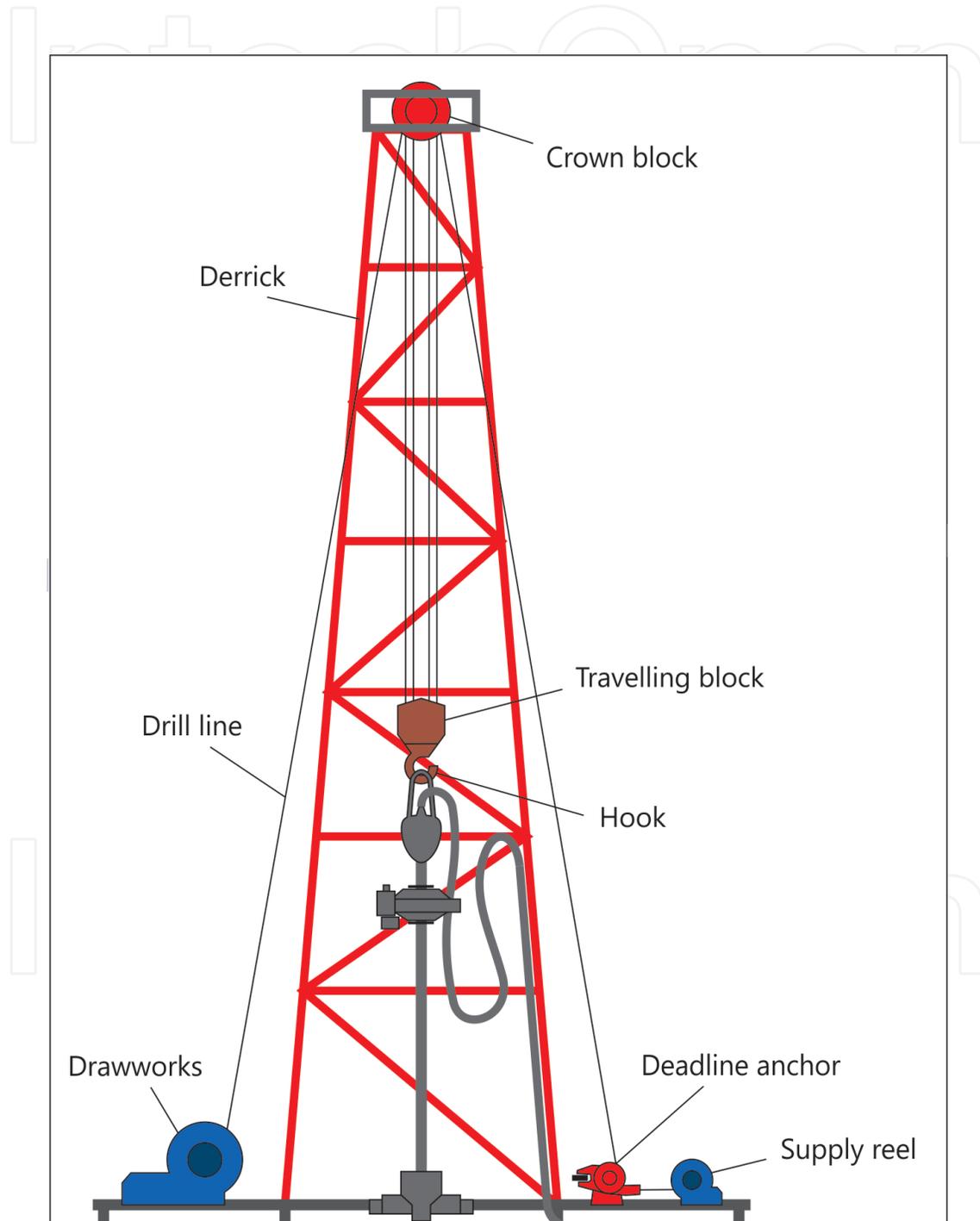
**Derrick** is mainly used offshore and is a large load-bearing vertical structure, usually of bolted construction and pyramidal in shape, for the equipment used to lower and raise the drill string into and out of the wellbore. The height of the derrick does not affect its load-bearing capacity, but it shows the maximum length of the drill pipe section. The standard derrick has square-shaped rig floor with four legs standing at the corners of the substructure. It provides work space for the necessary equipment on the rig floor.

**Mast** is mainly used with onshore rigs and is a portable derrick that can be raised as unit but for the transporting can be divided into two or more sections. It is usually rectangular or trapezoidal in shape.

**Power and prime movers.** The power generated by the power system is used for five main operations such as rotating, hoisting, drilling fluid circulation, rig lighting and hydraulic systems. It is important to note that the most of the generated power is consumed by the hoisting and drilling fluid circulation systems. Internal combustion engine (mostly diesel) connected

to electric generators or turbine is the source of power on the rig. Some rotary rigs can use electricity directly from power lines.

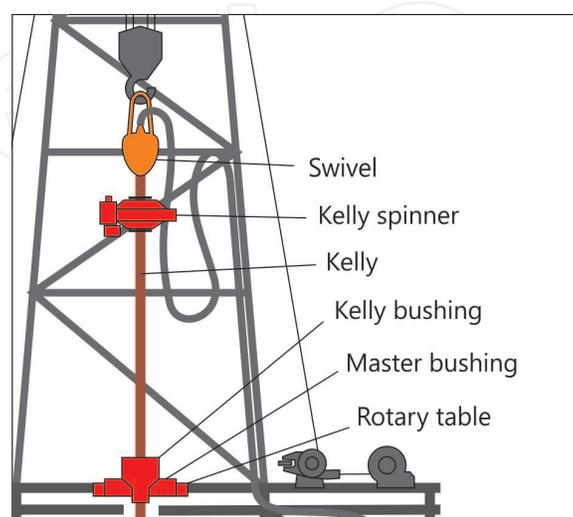
**Hoisting component** is used to perform all lifting activities on the rig and helps in lowering or raising equipment into or out of the well. It consists of drawworks, crown block, traveling block, deadline anchor, supply reel and drilling line (**Figure 4**).



**Figure 4.** Hoisting equipment of the drilling rig.

- **Drawworks** is the main operating component of the hoisting system and is used to transmit power from prime movers to the hoisting drum that lifts drill string, casing or tubing string out of and to lower it back into the borehole. They consist of a large diameter steel spool, brakes, a power source and assorted auxiliary devices. The primary function of the drawworks is to reel out and reel in the drill line, a large diameter wire rope, in a controlled manner. The speeds for hoisting the drill string could be changes by driller via integrated gear system.
- **Crown block** is fixed assembly of sheaves (single or double) with a wire rope drilling line running between it and is located at the top of the derrick or mast and over which the drilling line is threaded. It is used to change the direction of pull from the drawworks to the traveling block.
- **Traveling block and hook** combination is used to safely and efficiently raise or lower tools and equipment in the well. It is the set of sheaves or pulleys through which the drill line (wire rope) is threaded or reeved, is opposite the crown block and enabling heavy loads to be lifted out of or lowered into the wellbore. Hook is located beneath the traveling block and is used to pick up and secure the swivel and Kelly.
- **Deadline anchor** is usually bolted on to the substructure and is the equipment that holds down the deadline part of the wire rope. It provides weight measurements and secure deadlines.
- **Supply reel** is a spool that stores the unused portion of the drill line.
- **Drill line** is the wire rope used to support the drilling tools. It is threaded or reeved through the traveling block and crown block to facilitate the lowering and lifting of the drill string into and out of the borehole. Drill line then clamped to the rig floor by the deadline anchor.

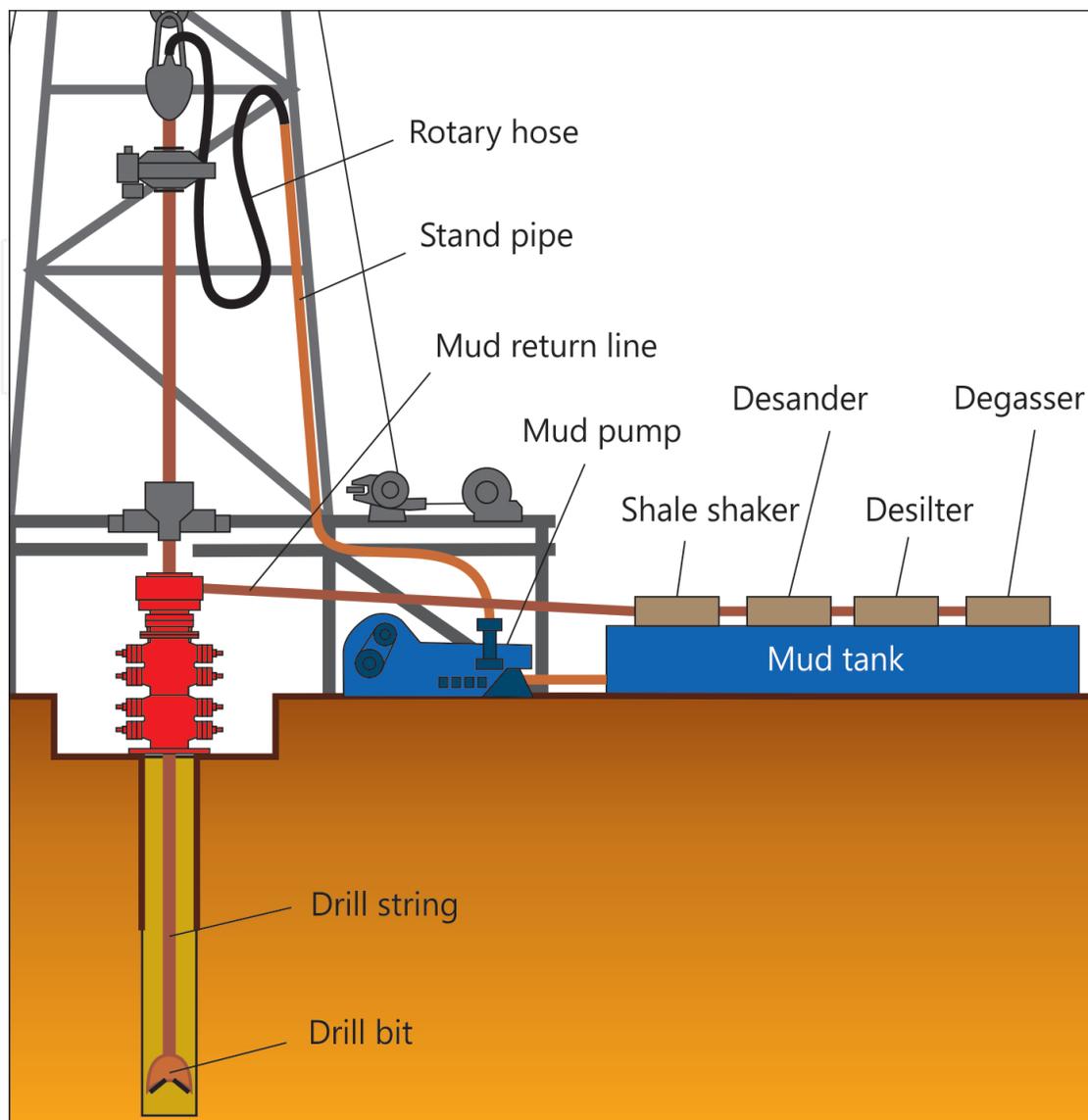
**Rotating component** is the equipment responsible for rotating the drill string. It consists of the swivel, Kelly spinner, Kelly or top drive, Kelly bushing, master bushing and rotary table (Figure 5).



**Figure 5.** Rotating equipment of the drilling rig.

- **Swivel** is a mechanical device that is hung from the hook of the traveling block to support the weight of the drill string and allows it to rotate freely. It provides connection for the rotary hose as well as passageway for the flow of drilling fluid into the drill stem.
- **Kelly spinner** is a pneumatically controlled device mounted below the swivel to spin the Kelly to make up tool joints when making connections.
- **Kelly** is the heavy steel square or hexagonal member that is suspended from the swivel through the rotary table and connected to the topmost joint of drill pipe to turn the drill stem as the rotary table turns. It has a hole drilled through the middle that permits fluid to be circulated into the drill stem and up the annulus or vice versa. The Kelly goes through the Kelly bushing, which is driven by the rotary table.
- **Top drive** is a hydraulically powered device on the drilling rig and is located at the swivel place. It allows the drill stem to spin and facilitate the process of drilling a borehole. Top drive means a power swivel, which directly turns the drill string without need for a Kelly and rotary table.
- **Kelly bushing** is a device that fits into a part of rotary table called master bushing, transmits torque to the Kelly and simultaneously permits vertical movement of the Kelly to make hole. The Kelly bushing as Kelly is square or hexagonal and has an inside profile matching the Kelly's outside profile with slightly larger dimensions so that the Kelly can freely move up and down inside.
- **Master bushing** is a tool that fits into the rotary table of a drilling rig to accommodate the slips and drive the Kelly bushing so that the rotating motion of the rotary table can be transmitted to the Kelly.
- **Rotary table** is section of the drill floor used to turn the drill stem. It has a beveled gear arrangement to create the rotational motion and opening into which bushings are fitted to drive and support the drilling assembly.

**Circulating component** is the rig equipment responsible for the movement of drilling fluid within the well as well as solids removal incurred by the drilling fluid (**Figure 6**). Normally, the circulation would start from the mud pits or tanks that are located besides the rig. Powerful pumps force the drilling through the surface high-pressure connections to a set of valves called pump manifold, located at the derrick floor. Then, the fluid goes up the rig within a pipe called standpipe to approximately 1/3 of the height of the mast. From there, the drilling fluid flows through a flexible high-pressure rotary hose to the top of the drill string. The flexible hose allows the fluid to flow continuously as the drill string moves up and down during normal drilling operations. The fluid enters in the drill string through a special piece of equipment called swivel located at the top of the Kelly. The swivel permits rotating the drill string while the fluid is pumped through the drill string. In wellbore, the drilling fluid then flows down the rotating string and jets out through the nozzles in the drill bit at the bottom of the hole. Drilling fluid carrying the drilled cuttings and flows out the center of the drill bit and is forced back up the outside of the drill pipe between the drill string and walls of the well (annular) onto the surface of the ground where it is cleaned and circulated back to the well. The cleaning process starts from the shale shaker, which is basically a vibrating screen.



**Figure 6.** Circulation system of the drilling rig.

This will remove the larger particles, while allowing the residue to pass into settling tanks. The finer material can be removed using other solids removal equipments such as desander and desilter. If the mud contains gas from the formation, it will be passed through a degasser that separates the gas from the liquid mud. Having passed through all the mud processing equipment, the mud is returned to the mud pits or tanks for recycling.

The principal components of the drilling fluid circulation system are as follows:

- **Mud pump** is a large, high-pressure and high-volume pump used to circulate the drilling fluid down the drill pipe and out of the annulus on an oil rig. It could be double acting duplex (2 cylinder) pump, which has four pumping actions per pump cycle or single acting triplex (3 cylinder) with three pumping actions per pump cycle whose pistons or plungers travel in replaceable liners and are driven by a crankshaft actuated by an engine or motor.

- **Pump manifold** is an arrangement of piping and valves that receives drilling fluid from mud pumps and transmits the drilling fluid to the succeeding circulating component. It is designed to control, distribute and monitor drilling fluid flow.
- **Stand pipe** is the vertical rigid pipe rising along the side of the derrick or mast, which joins mud pump manifold to the rotary hose.
- **Drill string** is the mechanical assemblage connecting the rotary drive on the surface to the drilling bit on bottom of the wellbore.
- **Mud return line or flow line** is the large diameter metal pipe and is the passageway of the drilling fluid as it comes out of the well.
- **Shale shaker** is the primary solids-removing device with one or more vibrating screens, which is used to remove cuttings from the circulating fluid for reuse. Screens vibrate while the mud flows on top of it. The liquid phase with solids which are smaller than the wire mesh pass through the screen as well as larger solids are retained on the screen and eventually fall to the special container and can be disposed in an environmentally friendly manner.
- **Desander** is a centrifugal device for removing sand-size particles from the drilling fluid to prevent abrasion of the pumps. There are no moving parts of a desander, and the removal of particles is done by gravity and pressure. As the drilling fluid flows around and gradually down the inside of the cone shape, particles are separated from the liquid by centrifugal forces.
- **Desilter** is also a centrifugal device for removing free particles of silt from the drilling fluid. Comparing with desander, its design incorporates a greater number of smaller cones, which allow removing smaller diameter particles than a desander does.
- **Degasser** is device designed to remove air, methane, hydrogen sulfide (H<sub>2</sub>S), carbon dioxide (CO<sub>2</sub>) and other gases from drilling fluids and allow it to be reused continuously. It helps to reduce the risk of explosions and other dangers during the drilling process.
- **Mud pit** is an excavated earthen-walled pit and is used only to store used or waste drilling fluid and cuttings.
- **Mud tank** is an open-top steel container with possibility to observe the consistency of drilling fluid and monitor its level in the tanks. It is used as a reserve store for the drilling fluid.

**Tubular and tubular handling equipment.** Tubular consists of the following equipments:

- **Drill pipe** is the longest section of the drill string and is heavy hot-rolled, pierced and seamlessly tubing. It connects the surface equipment with the bottom hole assembly and the bit is used to rotate the bit and for drilling fluid circulation.
- **Drill collar** is thick-walled, heavy and large diameter steel tube placed between the drill pipe and the bit in the drill stem to provide weight on a bit. It can be cylindrical or spiral shape and is threaded at both ends (male and female) to allow multiple drill collars to be joined above the bit assembly.
- **Heavy weight drill pipe** is thick-walled tube and is used as transition pipe between drill collar and drill pipe. In high-angled and horizontal wellbore, it is used in lieu of drill collars.

- **Subs** are short component of the drill string, threaded piece of pipe used to adapt parts of the drilling string that cannot otherwise be screwed together because of difference in thread size or design.

Tubular handling equipment is made of the following equipments:

- **Elevator** clamps that grip a stand of casing, tubing, drill pipe or drill collars so that the stand or joint can be lifted and lowered into the wellbore opening of the rotary table. The elevators are connected to the traveling block by means of bails, which are solid steel bars with eyes at both sides. Elevator could be side door, center latch or single joint types.
- **Elevator links** is device designed to support the elevators and attach them to the hook.
- **Slips** are a wedge-shaped piece of metal with teeth or other gripping elements that supports and transmits the weight of the drill string to the rotary table and are used to hold the pipe in place as well as to prevent pipe from slipping down into borehole. Different types of slips are used during oil well drilling such as drill pipe, drill collar or casing slips.
- **Safety clamp** is a mechanical device used on tubulars above the slips and is used to keep parts of the tool string from falling down the wellbore if other safety measures fail.
- **Tongs** are large wrenches used to make or break out tubular. It must be used in opposing pairs—make up or breakout tongs to make or break connection.
- **Drill pipe spinner** is a pneumatically operated device usually suspended on the rig floor used to make fast connections and spin off of drill pipe.
- **Iron roughneck** is a pneumatically operated machine that replaces the functions performed by the Kelly spinner, drill pipe spinner and tongs and is used to connect and disconnect tubular.

**Drill bits** are cutting tools used to create cylindrical holes. Bits are located at the bottom of the drill string and are suited for particular conditions, such as formation, which is to be drilled. There are three different types of bit designs, such as:

- Roller cone bits with milled tooth or tungsten carbide insert (TCI) could have 2–6 cone-shaped steel devices that are free to turn as the bit rotates.
- Fixed cutter bits could be drill bit or core bit. The first one could be polycrystalline diamond compact bit (PDC-bit), surface set diamond bit and impregnated diamond bit. It consists of bit bodies and cutting elements integrated with the bit bodies and do not have moving parts.
- Hybrid bits combine both rolling cutter and fixed cutter elements.

If the drill bit needs to be changed, the whole string of pipe must be raised to the surface.

### 3. Classification of the drilling fluids

Modern drilling fluids (muds) are complex heterogeneous fluids (water based, oil based) and are complex mixtures of more than 200 minerals and chemicals. It is used in a drilling operation

and circulates from the surface, down the drill string, through the bit and back to the surface via the annulus. The original use of the drilling fluids was to remove cuttings continuously. Progress in drilling engineering demanded more sophistication from the drilling mud. In order to enhance the usage of drilling fluids, numerous additives were introduced and a simple fluid became a complicated mixture of liquids, solids and chemicals. As the drilling fluids evolved, their design changed to have common characteristic features that aid in safe, economic and satisfactory completion of a well. In addition, drilling fluids are also now required to perform following functions:

- Clean the rock formation beneath the bit for rock cuttings.
- Remove cutting from the well.
- Control formation pressures while drilling and maintain wellbore stability.
- Suspend and release cuttings.
- Seal permeable formations to prevent excessive mud loss.
- Minimize reservoir damage by using reservoir drill-in fluid.
- Cool, lubricate and clean the bit and drilling assembly.
- Transmit hydraulic energy to downhole assembly.
- Ensure adequate formation evaluation.
- Control corrosion.
- Facilitate downhole measurement (measurement while drilling, logging while drilling).
- Facilitate cementing and completion.
- Minimize impact on the environment.

However, excessive use of oil-based drilling fluids may harm the environment and it is important to develop more environmentally friendly drilling fluids. In this respect, water-based drilling fluids are more acceptable. As well known, bentonite is widely applied in the water-based drilling fluids, which could enhance the clean properties and form a thin filter with low permeability. The functions of bentonite are to make the fluids more viscous and reduce the loss of fluids.

There are four types of drilling fluids (**Figure 7**):

1. **Water-based drilling fluid (WBM)** is the mud in which water is continuous phase. The water could be fresh, brackish or seawater. The most basic WBM system begins with water, then clays and other chemical and is incorporated into the water to create a homogenous blend. The clay (called "shale" in its rock form or bentonite) is frequently referred to in the oilfield as "gel." Many other chemicals (e.g. potassium formate,  $\text{KHCO}_2$ ) are added to a WBM system to achieve various effects, including velocity control, shale stability, enhance drilling rate of penetration, cooling and lubricating of equipment [2–4].

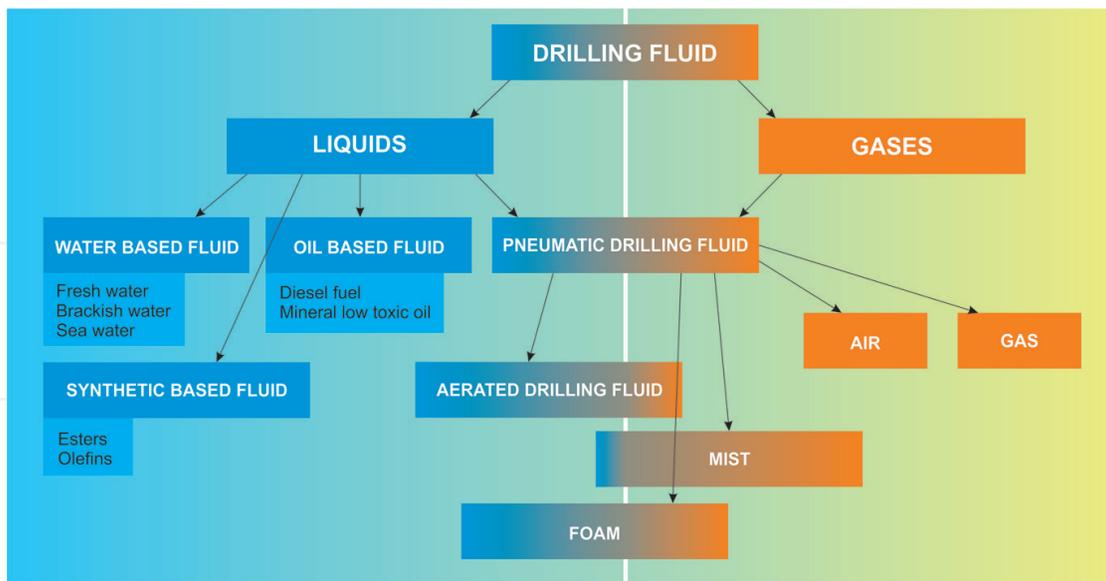


Figure 7. Classification of the drilling fluids.

### Advantages

- Low cost
- High rate of penetration
- Good cuttings removal
- Good geoscientific investigations
- The pressure in the cutting area increases with increasing hydrostatic pressure of drilling fluid.

### Disadvantages

- Low borehole stability [5]
- Insufficient cutting transport efficiency
- Insufficient lubricating properties
- Drilling fluid loss.

2. **Oil-based drilling fluid** has best technical properties such as stability, lubricity and temperature stability. Oil-based mud can be a mud where the base fluid is a petroleum product such as diesel fuel or mineral low toxic oil. The authorities do not permit the discharge of oil-based drilling fluid and cuttings drilled with oil-based drilling fluids because of their special nature of being a mixture of two immiscible liquids (oil and water). In that case special treatment and testing are required. The terms oil-based mud and inverted or invert-emulsion mud used to distinguish among the different types of oil-based drilling fluids. Traditionally, an oil-based mud is a fluid with 0–5% by volume of water, whereas an invert-emulsion mud contains more than 5% by volume of water.

### Advantages

- Excellent lubricating properties (reduce drilling torque and drag)
- Good temperature stability
- Favorable to borehole stability
- High rate of penetration
- Will not hydrate clays
- Long bit life
- Low reservoir damage
- Low drilling fluid loss
- Salt not dissolved
- Corrosion resistance
- Can be reused.

### Disadvantages

- High initial cost
- Electric log difficulty
- Viscosity varies with temperature
- Environmental issue
- Difficult to keep the rig clean while drilling
- Difficult to identify gas kick
- Messy working environment
- Fire hazards.

3. **Synthetic drilling fluids** are based on ether, ester or olefin. They have technical properties that are similar to oil-based drilling fluids and are most often used on offshore rigs or in environmentally sensitive areas, because it has the properties of an oil-based mud, but the toxicity of the fluid fumes is much less than an oil-based fluid. This is often used on offshore rigs.

### Advantages

- Favorable to borehole stability
- High rate of penetration
- Good wellbore stability
- Good control of drilling fluid properties

- Good cutting transport efficiency and removal
- Good filtration properties.

#### Disadvantages

- Complex system with high solid content
- Geoscientific investigations difficulty.

**4. Pneumatic drilling fluids**—Fluids, which are based on air/gas, mist, aerated fluid or foam. Air drilling is used primarily in hard rock areas and in special cases to prevent formation damage while drilling into production zones or to circumvent severe lost-circulation problems. Air drilling includes dry air drilling, mist or foam drilling and aerated mud drilling. In dry air drilling, dry air/gas is injected into the standpipe at a volume and rate sufficient to achieve the annular velocities needed to clean the hole of cuttings. Mist drilling is used when water or oil sands are encountered that produce more fluid than can be dried up using dry air drilling. A mixture of foaming agent and water injected into the air stream, producing foam that separates the cuttings and helps remove fluid from the borehole. In aerated mud drilling, both mud and air pumped into the standpipe at the same time. Aerated mud is used when it is impossible to drill with air alone because of water sands and/or lost-circulation situations.

#### Advantages

- High rate of penetration
- Low reservoir damage
- Good bit performance
- Low drilling fluid loss
- Low water consumption
- Low air quality requirements for foam drilling
- Low hydrostatic pressure
- Good cleaning of the borehole.

#### Disadvantages

- There are restrictions on the possible lithological structures
- Drilling could be limited by the length of the horizontal section of the well
- Possibility of fire
- Possible additional costs to rent equipment
- Gas costs
- Gas and foam utilization issues

- Aerated fluids require specialized equipment for the injections
- Aerated fluids and foam have potential corrosion problems and the need to use additional inhibitor
- The quality of the foam changes in exchange pressure
- The foam is a complicated system and may require computer modeling of foam movement in the borehole.

### 3.1. Mud ingredients

Various materials may be added at the surface to change or modify the characteristics of the mud:

1. **Weighting materials** (usually barite) are added to increase the density of the mud, which helps to control subsurface pressures and build the filter cake. Salts are sometimes added to protect downhole formations or to protect the mud against future contamination, as well as to increase density. Dispersants or deflocculants may be added to thin the mud, which helps to reduce surge, swab and circulating pressure problems.
2. **Viscosifying materials** (clays, polymers and emulsified liquids) are added to thicken the mud and increase its hole cleaning ability. [6]
3. **Filtration control materials.** Clays, polymers, starches, dispersants and asphaltic materials may be added to reduce filtration of the mud through the borehole wall. This reduces formation damage, differential sticking and problems in log interpretation.
4. **pH control and lubricating materials.** Mud additives may include lubricants, corrosion inhibitors, chemicals that tie up calcium ions and flocculants to aid in the removal of cuttings at the surface. Caustic soda is often added to increase the pH of the mud, which improves the performance of dispersants and reduces corrosion.
5. **Other additives.** Preservatives, bactericides, emulsifiers and temperature extenders may all be added to make other additives work better.

Most of these additives have distinct properties that help in countering specific challenges encountered during the drilling process as well as in accomplishing the drilling work with efficiency and precision [7]. However, to select the proper fluid, it is necessary to calculate the cost of the fluid, understand the environmental impact of using the fluid and to know the impact of the fluid on production from the pay zone.

## 4. Drilling mud losses and its prevention

The complex drilling fluids represent 15–18% of the total cost of petroleum well drilling. Lost circulation is major problem in the drilling operations and is defined as the loss of drilling fluid through the pores or fissures in the rock formations to be drilled, sometimes referred

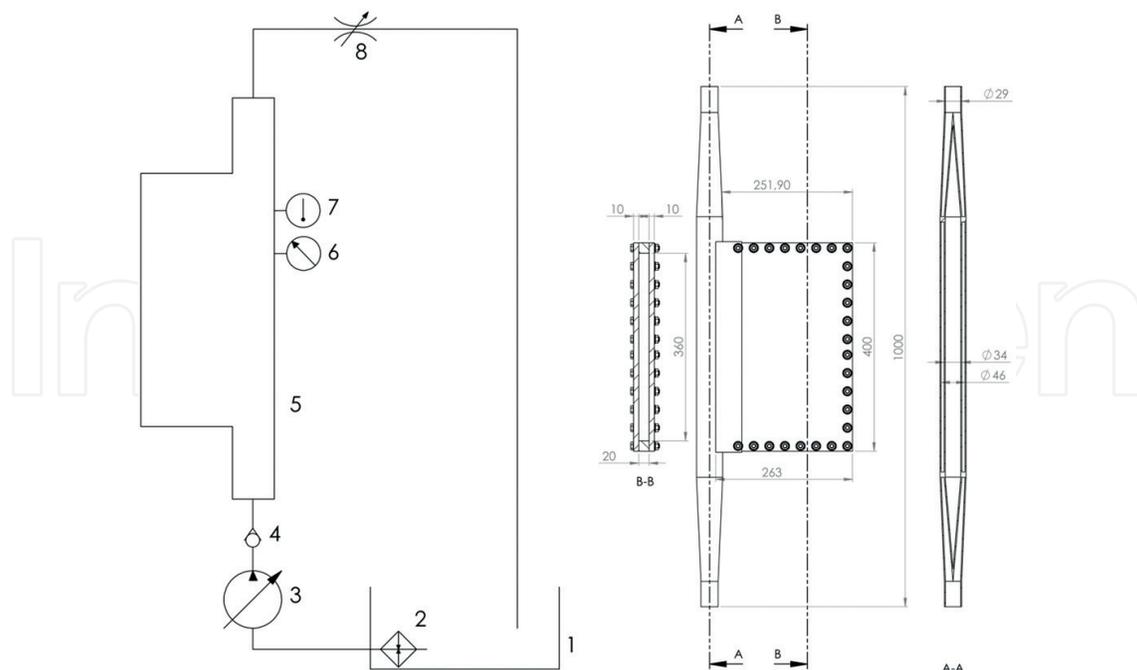
to as “thief zones.” It occurs when hydrostatic pressure of fluid column in the wellbore is higher than the formation pressure and is defined as the loss of drilling fluid into the formation. Lost circulation influences directly effect the non-productive time, a drilling operation that includes the cost of time and all services that support the drilling operation. It is usually accompanied by wellbore stability problems, which can result in stuck pipe and even the loss of the well [8–10].

The fluid loss of circulation is most commonly responsible for 10–20% of the total cost of a productive or an exploration well. Well bore costs, in turn, represent 35–50% of the total capital costs of a geothermal typical project; therefore, about 3.5–10% of the total costs can be attributed to the loss of circulation [11].

#### 4.1. Physical simulator of flow in the formation

The physical simulator of flow in the formation (SFF) device allows determining the mud loss to the formation. It consists of a fluid storage tank with mixer, well-simulated pipe with formation packing system, pump, temperature and pressure-measuring device and so on.

An experimental procedure was developed with the purpose of studying effects of additives and loss circulation material on mud loss to the formation. The mud sample that was prepared and mixed in the separate storage tank transferred into the stand’s storage tank (1) (**Figure 8**). Formation packing system was filled with the formation that was tested against the drilling mud. Then, the formation packing system connected to the well-simulated pipe (5). The hollow cable from the pump (3) is connected to the compressor to make the pump run



**Figure 8.** Kinematic scheme of the physical simulator of flow in the formation: 1—fluid storage tank with mixer; 2—heater; 3—pump; 4—valve; 5—well-simulated pipe with formation packing system; 6—pressure measuring device; 7—temperature measuring device and 8—pressure regulator.

at desired pressure. After the pump has been turned on, the drilling mud started to circulate from the storage tank through the well-simulated pipe. The process runs for 30 minutes and when it is finished it is possible to measure the fluid penetration rate.

The visualization of the physical simulator of flow in the formation is shown in **Figure 9**.

Combating loss by the proper use of reinforcement materials of wells, well strengthening and loss circulation materials is fundamental for a successful drilling [12–14]. In **Figure 10**, simulation results (Flow 3D) show the influence of the loss circulation materials on the drilling process. In case of the water drilling, the drilling fluid losses are significant, whereas in case of the loss circulation materials, rate of penetration considerably decreases.

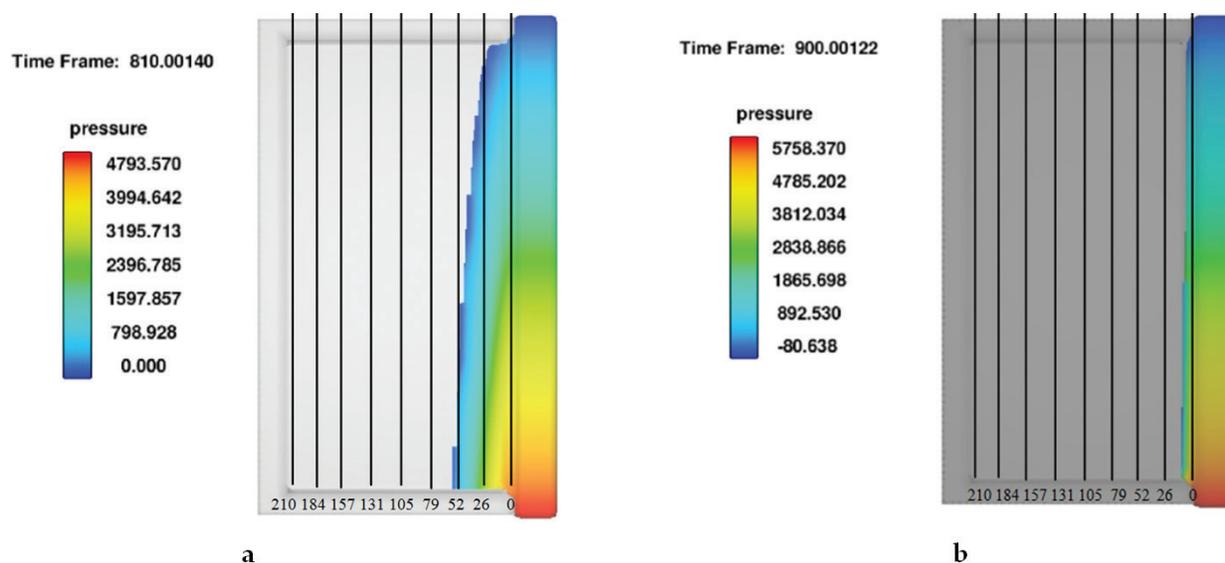
Industries use coke, attapulgite, nutshells, mica flakes, cellulose nanoparticles and other materials to mitigate the loss of circulation [15]. The use of such materials increases the cost of drilling, but by using the materials such as cotton, sawdust and used oil would employ the same purpose in most cost-effective and eco-friendly way.

Various materials such as cotton waste, used oil, saw dust etc. are commonly employed as fluids loss control agent. The evaluation of the rate of penetration of various mud samples to the formation proposes an effective way to minimize the mud loss by forming a static filter cake on the walls by changing the components of the water-based drilling fluid.

It is important to evaluate the amount of drilling fluid loss to the formation and to overcome it by forming a static filter cake on the borehole walls by changing the components of the water-based drilling fluid [16, 17].



**Figure 9.** Visualization of physical simulator of flow in the formation.



**Figure 10.** Comparison of the fluid loss and rate of the penetration by pure water and the water-based fluid drilling: a—water; b—drilling fluid.

#### 4.2. Preparation of mud samples and properties of the formation

Formation porosity directly affects the mud loss, if the pore size of the formation is high, it means that the formation pore size do have much space to retain any fluid or small particle which passes through it [18]. During the experiment, the density of the formation was  $1.606 \text{ g}\cdot\text{cm}^{-3}$ . The pH of the formation was 8.73 and is alkaline, so it will not play a vital on altering any significant property of the drilling mud. Humidity does not play a major role in mud loss, but it has to be measured to determine the filtration property of the sand. Humidity of formation was 4.26%.

Base mud sample, containing only water and bentonite clay, was prepared by adding 720 g of bentonite to 12 liters of water to obtain a bentonite mass fraction of 5.66% and a bentonite-to-water ratio of 6% (**Figure 11**).

The bentonite-to-water ratio was maintained constant for all subsequent mud samples used in this research.

All mud samples were prepared at ambient conditions (at  $17^\circ\text{C}$  or  $62.6^\circ\text{F}$ ). Respectively, their density and rheological properties were measured. Sodium hydroxide (NaOH) was used to adjust the pH of mud samples to ensure that each sample has same pH value of 10.85. Potassium chloride (KCl) was used as a clayish rock swelling inhibitor because the loam formation used during the research has clay content and was constant for all mud samples. Sodium carbonate (NaOH) was used to regulate the calcium concentration in the drilling mud.

Mud samples with varying additive concentrations and loss circulation materials such as saw dust, waste cotton and used oil were prepared as it is shown in **Table 1**.

The water-based mud samples presented in **Table 1** are named according to the loss circulation materials added to it. For instance, the mud sample with sawdust is named from S1 to S3



**Figure 11.** Prepared mud sample.

according to the weight of the material present in it. The sawdust was added from 232 to 522 g in three mud samples and cotton is added from 25 to 75 g in C1–C3. The used oil was added in milliliter and their relative weight of oil was calculated and presented in g. The used oil was added from 135 to 404 g to O1 to O3 mud samples.

In this experiment, rheological properties of drilling mud additives were studied (**Table 2**). Mud samples with a varying concentration of additives were prepared; their properties were studied and compared.

Mud samples		Mass of water	Mass of bentonite	Mass of Na <sub>2</sub> CO <sub>3</sub>	Mass of NaOH	Mass of saw dust	Mass of waste cotton	Mass of used oil
		Kg	g	g	g	g	g	g
Bentonite	B1	12	720	60	14.4	0	0	0
Sawdust	S1			68	17.2	232	0	0
	S2			70.5	19	397	0	0
	S3			74.2	20.5	522	0	0
Cotton	C1			61	17.8	0	25	0
	C2			63.2	18.05	0	50	0
	C3			66.6	18.60	0	75	0
Used oil	O1			60	23.4	0	0	135
	O2			63.7	24.2	0	0	269
	O3			66.6	24.8	0	0	404

**Table 1.** The composition of water-based mud samples.

Mud samples		Mud density	Plastic viscosity	Yield point	10-sec gel strength
		lb/gal	cP	lb/100 ft <sup>2</sup>	lb/100 ft <sup>2</sup>
Bentonite	B1	9.260	18	18	4
Sawdust	S1	9.290	23	25	6
	S2	9.290	24	28	7
	S3	9.296	26	31	9
Cotton	C1	10.26	29	33	16
	C2	10.43	35	35	24
	C3	10.68	37	43	31
Used oil	O1	9.280	20	21	5
	O2	9.280	21	24	6
	O3	9.296	22	26	8

**Table 2.** Variation of the muds' rheological properties by using additives.

The **mud density** comparison of all three mud indicated that a cotton-based mud will give a higher mud density than the other two (10.26–10.68 lb/gal). This is because of the higher specific gravity of cotton as it greater than of saw dust and oil. In addition to its use as loss circulation materials, cotton-based mud can also act as weighting agent. To prevent the flow of formation fluids into the hole, the drilling mud must exert a greater pressure than that of the fluids in the porous rocks that are penetrated by the bit. In that case, the cotton-based mud with slightly high density can act as an effective loss circulation materials.

**Plastic viscosity (PV).** The experiment results show that the mud samples with sawdust and cotton have high viscosity ranging from 23 to 26 cP in the case of saw dust and 29 to 37 cP in the case of cotton. This is due to the fact that the mud with considerable suspended particle will always have high plastic viscosity as well as the force existing between the particles and the force between the particles and the liquid. So, this result indicates that the mud samples with cotton and sawdust have much high solid content as 75 g in cotton and 522 g in sawdust and always depend upon the concentration of mud solids.

**Yield point (YP)** is used to evaluate the ability of mud to lift cuttings out of the annulus. When the yield point is higher, the mud loss inside the fracture is less. The shear stress required to initiate the flow of mud also increases as the yield point increases. Over time, this yield point helps in preventing the mud from flowing further into the fracture, which leads eventually to it becoming plugged [19]. A higher YP implies that drilling fluid has ability to carry cuttings better than a fluid of similar density but lower YP. From the above result, compare the mud samples S3 and O3, in both mud samples, the density is quite the same, it is 9.296 lb/gal, whereas the YP of S3 is 5% greater than O3. In this case, the S3 mud sample will work better in carrying cuttings than O3. The bentonite (B1) sample is taken as a reference sample.

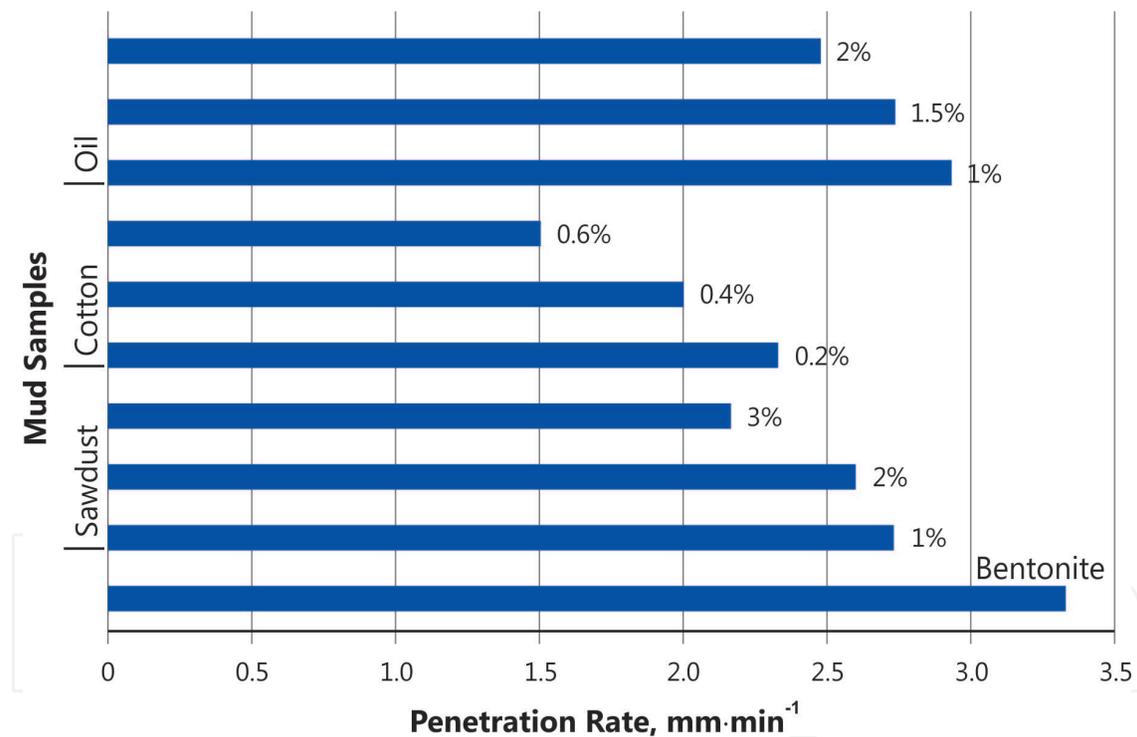
**10-sec gel strength results.** The gel strength is one of the important drilling fluid properties because it demonstrates the ability of the drilling mud to suspend drill solid and weighting

material when circulation is ceased. The results were achieved based on standard API procedure. It is investigated that the mud sample with cotton as a loss circulation materials has gel strength twice higher than the other two. It means that it will work well in the case of suspending drill cutting when the circulation is halt for 1 to 2 days.

The rate of penetration of all mud samples is represented in **Figure 12**.

**Figure 12** consolidates all the result obtained from the experimental work. In the case of sawdust mud sample, the weight percentage of sawdust added were ranging from 1 to 3%, and in the case of used oil, it is 1, 1.5, 2%, but in the case of cotton, it is just 0.2, 0.4, 0.6% because the cotton make the mud more viscous and heavily dense, which makes it hard for the pump to deliver the same pump rate as it was done with sawdust and used oil mud samples. From **Figure 12**, it is evident that the mud samples with additives can be used as loss circulation material during oil well drilling.

In this work, it is evident that the prepared and tested mud samples work well with the unconsolidated coarse-grained formation in terms of mud loss.



**Figure 12.** Rate of penetration of all mud samples in formation.

## 5. Conclusions

The concentration of loss circulation material is vital to control the rheological properties of drilling mud. Significant changes in mud density, plastic viscosity, yield point and gel strength were noted to correspond to changes in the concentration of mud loss circulation material.

Water-based mud with cotton as loss circulation material gave a remarkably higher value of density, yield point, gel strength and plastic viscosity when used at lesser concentration than sawdust and used oil. Moreover, water-based mud samples with cotton having the least penetration rate. The lack of loss circulation material could result in significant mud loss.

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