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REVIEW ARTICLE - PETROLEUM ENGINEERING

Deep Illustration for Loss of Circulation While Drilling

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Abstract

One of the most severe, costly, and time-consuming problems in the drilling operation is the loss of circulation. The drilling fluid accounts for 25–40% of the total cost of the drilling operation. Loss of the drilling fluid will increase the total cost of the drilling operation. Uncontrolled lost circulation of the drilling fluid may result in dangerous well control problem and in some cases the loss of the well. Fluid losses can occur in different formations such as natural fracture, induced fracture, unconsolidated, and cavernous and vugular. The objective of this paper is to deeply understand and illustrate different types of loss of circulation, techniques used to determine the loss rate, and detection of loss zones. In addition, losses mitigation techniques, different lost circulation materials (LCM), and the apparatus used to evaluate the available LCM will be explained in detail. The deep literature review illustrated that lost circulation costs 10–20% of the cost of drilling high-pressure high-temperature wells and 90% of these losses occur in fractured formations. The loss rate depends on the drilling fluid types, and it is generally higher in the case of water-based drilling fluid than in the case of oil-based drilling fluid. It is important to utilize an advanced measurement for losses with high frequency to detect the occurrences of lost circulation quickly and correctly. The measurements of flow rate (flow in and flow out) should be supported by additional data such as logging data, lost circulation information (loss rate and depth), mud properties, and surface drilling parameters. The preventive approach is the most efficient to mitigate the loss of circulation since the use of conventional LCM is not successful in most of the cases because of their limitations. It is vital to consider the size of different fractures encountered while drilling and modify the laboratory equipment to simulate this problem. Loss of circulation is affected by many parameters that are related to formation characterization, drilling parameters, fluid properties, and a lot of other known and unknown factors. Therefore, it is a challenge to predict the loss of circulation. To overcome such challenge, it is recommended to develop a new technique such as artificial intelligence to predict the thief zones and the loss rate by capturing the changes in the drilling mechanical parameters and the fluid properties.

Keywords Loss of circulation · Drilling fluid · Lost circulation material · Drilling cost

1 Introduction

Loss of circulation or loss of return is known as the partial or complete loss of the drilling fluid from the annulus into the formation at any depth when using an overbalanced drilling technique [1]. There are two necessary conditions for the occurrence of circulation loss: the wellbore pressure must be greater than the fracture pressure and the availability of flow pathways for losses to occur [2, 3].

Drilling mud components are very expensive and cost the petroleum industry around $12.31 billion in 2018 as indicated by the drilling mud global market [4]. In addition to the high cost of the drilling operation which resulted from mud losses, uncontrolled lost circulation of the

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drilling fluid can result in dangerous well control problem and in some cases the loss of the well [5].

Different techniques are used to treat loss of circulation problem while drilling and workover operations. The first step is to adjust the drilling fluid properties to decrease the equivalent circulation density (ECD) and, as a result, reduce the volume of lost drilling fluid to the formation [2, 6]. ECD represents the mud density and annular pressure loss. The second step is to use solid particles, which are referred to as lost circulation material (LCM) to reduce and prevent loss of circulation. The common LCM includes flaky, granular, fibrous, blended, water/acid-soluble, hydratable/swellable LCM, nanoparticles, cement plug, polyurethane grouting, settable plugs, cross-linked gel, and viscoelastic surfactant [7–10].

Each type of lost circulation material mentioned above has some advantages and disadvantages. Most of these treatments need time to be prepared and placed, while others need to be removed out of the hole to keep the tools safe [11]. In order to avoid lost circulation, some methods are introduced to identify the thief zones such as resistivity logs, temperature profile, and ECD [2, 6, 12, 13]. However, some of these methods are difficult to be applied because of financial issues and lack of technology. The conventional methods for loss of circulation detection are not accurate.

2 Types of Lost Circulation

Lost circulation is divided into four types based on the severity of the losses: seepage, partial, severe, and total losses [14].

2.1 Seepage Losses

Lost circulation is called seepage when losses are varying from 1 to 10 barrels per hour (bbl/h) under the dynamic condition and a loss rate ranging from 10 to 20 bbl/h under static condition [15]. The rate of seepage loss could be less than 10 bbl/h [16–20]. The loss rate changes based on the drilling fluid types; for water-based drilling fluid, the loss rate usually is less than 25 bbl/h, while for oil-based drilling fluid, the loss rate is less than 10 bbl/h.

Seepage loss occurs in different formations and it commonly occurs in permeable and porous formations where the formed filter cake while drilling is not impermeable [13]. Ferron et al. [21] stated that the main cause of seepage losses is the erosion of the filter cake because of the drilling cutting and the mud turbulent.

2.2 Partial Losses

Lost circulation is called partial or moderate loss when losses are varying from 10 to 50 bbl/h under the static condition and a loss rate of 10–20% of the drilling mud under dynamic condition [19, 22, 23]. Some researchers have defined the rate of partial loss to be between 10 and 500 bbl/h [18, 20, 24]. Other researchers have limited the loss rate to be ranged from 25 to 100 barrels per hour for water-based mud and 10 to 30 barrels per hour for oil-based muds [25]. According to Ivan et al. [26], the mud losses rate ranging from 10 to 25 barrels per hour is classified as partial losses. Partial loss can occur in unconsolidated sand, gravels, horizontal natural fracture, and vertical induced fracture [15, 18].

2.3 Severe Losses

Lost circulation is called severe when losses are varying from 50 to 150 bbl/h under the static condition and a loss rate of 50–100% of the drilling mud under dynamic condition [15, 19]; severe loss is also called a complete loss [18]. Some researchers defined the severe loss as the loss circulation associated with the loss of more than 500 bbl/h [18, 23, 24]. Other researchers have limited the loss rate to be more than 100 bbl/h for water-based mud and more than 30 bbl/h for oil-based muds [25]. According to Ivan et al. [26], the mud loss rate greater than 25 bbl/h is defined as severe losses. Severe loss can occur in long unconsolidated sand gravels, caverns, vugs, large induced, and natural fractures [18]. Caverns losses occur at shallow depths and are very hard to mitigate [21].

2.4 Total Losses

Lost circulation is called total loss when no return is detected at the surface [19, 20, 25]. It is also defined as a case where the drilling mud level in the annulus cannot be seen. Total loss can occur in cavernous, vugular, and very large fractures [18]. Some researchers consider the total and severe losses to be the same. Table 1 lists different types of lost circulation with their specific loss rate in oil and water base mud [25].

Table 1 Types of lost circulation [25]

Classification	Typical loss rate (bbl/h)	
	Oil-based mud	Water-based mud
Seepage	<10	<25
Partial	10–40	25–100
Severe	>40	>100
Total	No returns	No returns

3 Zones of Lost Circulation

Loss of circulation is expected to occur in any type of lithology and formations as this issue has been encountered in many rock types at different depths. Most of the lost circulation zones are defined based on the fracture length and shape. Some of the formations have more tendency to lose fluids such as natural fracture, unconsolidated zones, cavernous, vugular zones, and induced fracture. These formations are defined based on the path and speed of the fluid when it exits the wellbore [13].

3.1 Natural Fracture Zone

While drilling through limestone and chalk formations, which contain natural fractures [17, 27], the pit level is reduced gradually and slowly confirming the occurrence of losses. A total loss can occur when the drilling is continued are more fractures are exposed [28]. Figure 1a represents natural fracture zones.

3.2 Unconsolidated Zones

These zones include high-permeable and porous formations, micro-fractured carbonates, loose gravels, and unconsolidated sands [29]. Lost circulation through unconsolidated zones is detected by a slow drop of the pit level, and a total loss can be caused if drilling is continued [28]. They commonly have a permeability ranging from 10 to 100 Darcy and occur at shallow depths [22]. Figure 1b illustrates the unconsolidated zone in the high-permeable formation.

3.3 Cavernous and Vugular Zones

These zones are most commonly occurring in dolomite or limestone formations because of infiltrating water that dissolves calcium [13, 22]. The openings size in this zone is varying from an inch to large channels [17]. Lost circulation through cavernous zones is detected by a sudden and very fast increase in the rate of penetration (ROP) and maybe drop of the drillstring from many inches to several feet into the new zone before the occurrence of the loss. A sudden loss of drilling fluid is also another indication of the losses in the vugular formations which leads to a quick and complete lost circulation. These zones are considered the hardest formation to plug [13, 28]. Figure 1c illustrates the formation of cavernous vugs.

3.4 Induced Fracture

Induced fractures are commonly created in the weak zones located above the high-pressure zone where a high mud weight is used. They may also be initiated because of rough handling of the drilling tools, choke down or excessive backpressure [13]. At shallow depth, the fracture is usually horizontal, whereas deeper than 2500 ft the fracture is mostly vertical [22]. According to Dupriest et al. [30] and Zhong et al. [31], more than 90% of circulation loss is contributed to the induced fracture. Loss of return through induced fracture is evidenced by a rapid loss of level of drilling fluid in the pit, which causes a complete loss when drilling is continued [28].

4 Effects of Lost Circulation

Loss of circulation has many consequences that affect the drilling operation economically and efficiently such as the increasing the drilling cost and non-productive time, leading to poor hole cleaning condition, and causing well control problems.

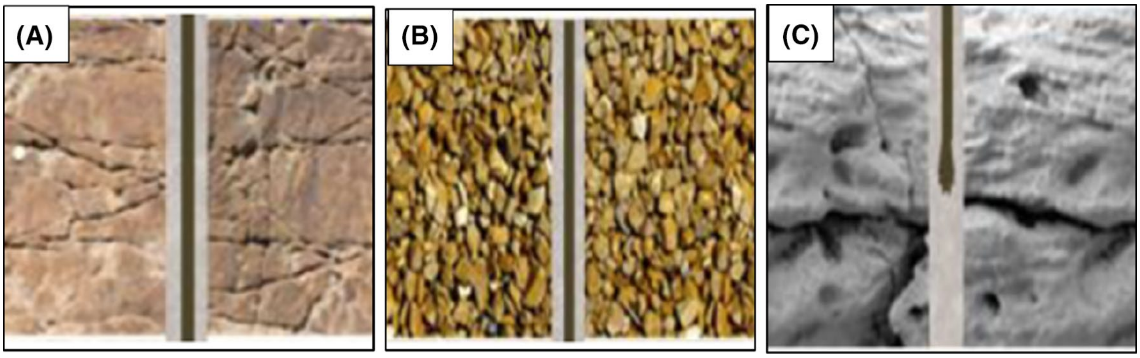

Fig. 1 Lost circulation in **a** natural fracture, **b** unconsolidated zone, **c** cavernous zone

4.1 Increasing the Non-productive Time

Solving the lost circulation problem takes long time where it is required to prepare a new pill with different lost circulation material and circulate the pill through the system; this will increase the non-productive time [32]. Lost circulation requires up to 3 days to control in onshore wells, whereas the number of days is increased in offshore wells to be up to 7 days [33]. From 1993 to 2003, in the Gulf of Mexico, more than 10% of the non-productive time is caused by fluid loss [34, 35]. A \$2–\$4 billion per year is estimated to be spent in the non-productive time because of the circulation loss [36]. Figure 2 shows that the loss of circulation is one of the most problems that require more time to be handled [37].

4.2 Poor Hole Cleaning

After a fluid loss has happened, the mud level is reduced inside the wellbore. As a result, mud will not be able to remove the cutting properly from the bottom to the surface of the well. This causes a poor hole cleaning particularly in directional drilling [38]. Consequently, poor hole cleaning will lead to cuttings accumulation at the bottom of the well which results in a stuck pipe and pack off [39, 40].

4.3 Increasing the Cost

Loss of drilling fluid is one of the most drilling problems that increase the financial cost. The annual cost of the problem is approximately \$1 billion [41, 42]. The treatment of fluid loss costs around \$200 million annually [26]. This cost contains lost drilling mud, lost time, and treatment costs [43]. The annual loss of the mud into the formation is approximated to be 1.8 million bbl [24, 44]. Lost circulation in onshore drilling operation costs approximately \$65,000 per day, whereas, in the offshore drilling operation, the cost is estimated to be doubled about (\$120,000) per day. In Canada and the USA, a well that suffers from circulation loss has a mud cost ranging from \$8000 to \$50,000 [45]. Circulation loss costs 10% to 20% of the price of drilling high-pressure high-temperature (HPHT) wells [46, 47].

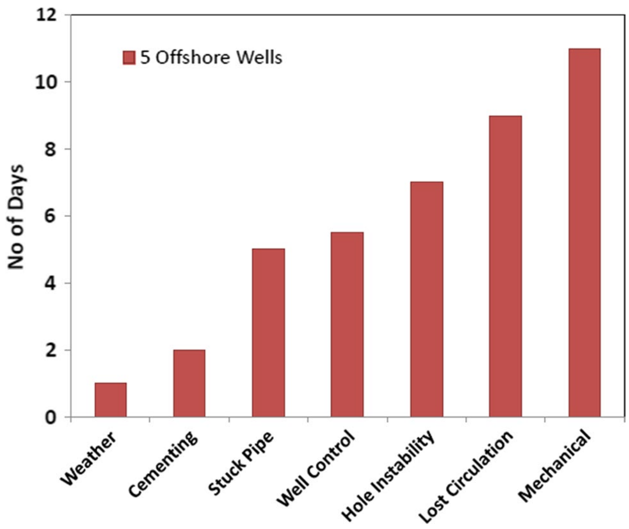

Fig. 2 Number of days required to control drilling problems [37]

4.4 Well Control Problem

After the occurrence of lost circulation, the mud level in the annulus is decreased which leads to a reduction in the hydrostatic pressure; this leads to the decrease in the wellbore pressure below the formation pressure. Consequently, a kick will happen because of the entrance of formation fluids into the wellbore, which might cause a blowout of the well [5].

5 Measuring the Loss of Circulations

The flow out (%) is the difference between the flow rate of the mud pumped inside the wellbore and the flow rate out of the well. This flow rate can be measured by two methods which are flowmeter and the pit level.

5.1 Flowmeter

Electromagnetic flowmeters are installed on the rig site to obtain high-frequency drilling fluid loss which gives complete information about the losses with the rate of sampling of 0.2 s^{-1} [2]. It has an accuracy of 10–15 l/min. The flowmeter that measures the flow rate inside the wellbore is placed on the standpipe, while the flowmeter that measures the flow rate coming out of the well is placed upstream the shakers [48]. The flowmeters could only be used with water-based mud because of their operational requirements of using electrically conductive drilling fluid [49]. Because of the poor quality of the mud coming out from the wellbore and its contamination with the drilled cuttings, the flowmeters measure the flow rate of the fluid coming out of the hole with less accuracy compared to the flowrate of the fluid flowing into the well.

5.2 Pit Level

Monitoring the pit level by floating or acoustic sensors is very important to indicate the cumulative quantity of the drilling fluid lost over a period of time. A decrease in the drilling fluid-pit level can refer to a significant loss of circulation [2]. Pit level has low accuracy in the detection of a small loss. Moreover, it is affected by many factors such as filling and draining of surface lines, losses in the surface, increasing and reduction of mud cycles due to pressure and temperature variations in the hole and the additives added to the mud such water or chemicals [2]. It is important to utilize an advanced measurement with high frequency to detect the occurrences of lost circulation quickly and correctly.

6 Detection of Losses Zones

Identifying the properties and the location of the zone of lost circulation (thief zone) is important to prevent lost circulation. Equivalent circulating density (ECD), propagation resistivity log, and temperature survey are the main measurements that can be used to identify the location of thief zones. There are also some indirect indications at the rig site that can be used to identify the location of the loss zone. For example, thief zone is considered to be at the drill bit when there is a notable change in the torque, penetration rate, and vibration [50].

6.1 Equivalent Circulating Density

Measuring the equivalent circulating density (ECD) while drilling can provide a sign of induced fracture existence. When the drilling fluid is circulated, there will be a rapid increase in ECD in the case of undamaged formation as shown in Fig. 3a, while in the case of fractured formation, the ECD increases slowly as shown in Fig. 3b. This gradual increase in ECD is due to the flow of the mud into the fracture [2]. On the other hand, when the circulation is stopped, there will be a rapid decrease in the ECD in the case of undamaged formation as shown in Fig. 4a, while in the case of fractured formation, the ECD drops gradually as shown in Fig. 4b. This slow decrease in the ECD is caused by the flow of the mud into the well coming from the fracture [6].

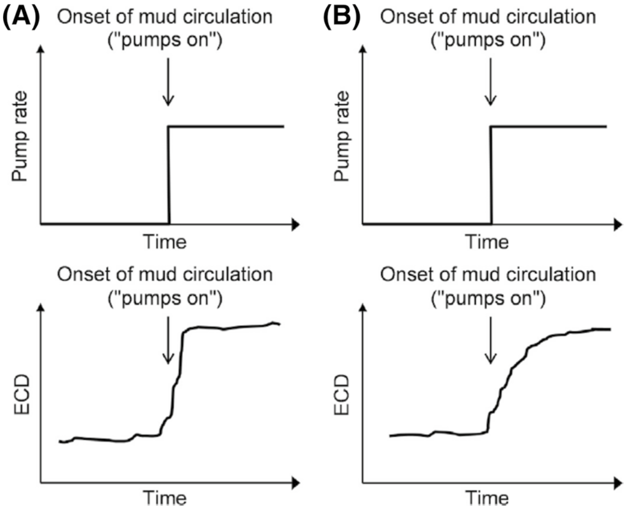

Fig. 3 Effects of lost circulation on ECD when mud is circulated [6]

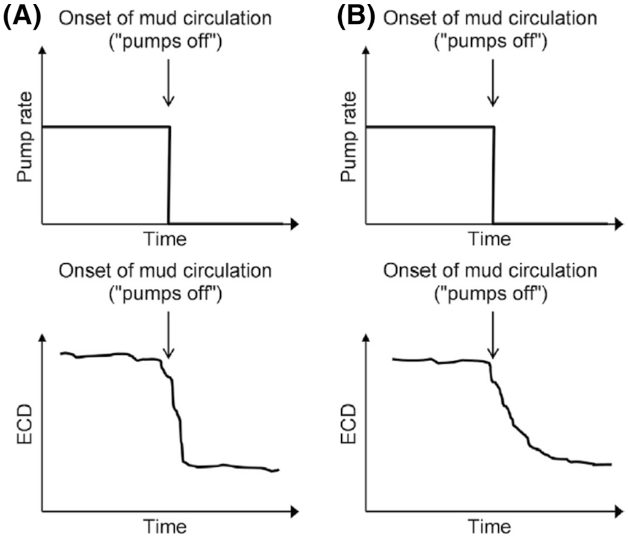

Fig. 4 Effects of lost circulation on ECD when circulation is stopped [6]

6.2 Propagation Resistivity Log

A propagation resistivity log can be useful in identifying the fracture height. This technique depends on two measurements: the first measurement provides information about the near-well area; the second measurement goes deeper into the formation [12]. A short fracture is indicated by a separation of the curves measured at the two depths [6]. The size of the fracture is estimated by the length of the separated interval as shown in Fig. 5 [12]. A long fracture is indicated by an increase in both curves of resistivity without separation as shown in Fig. 6.

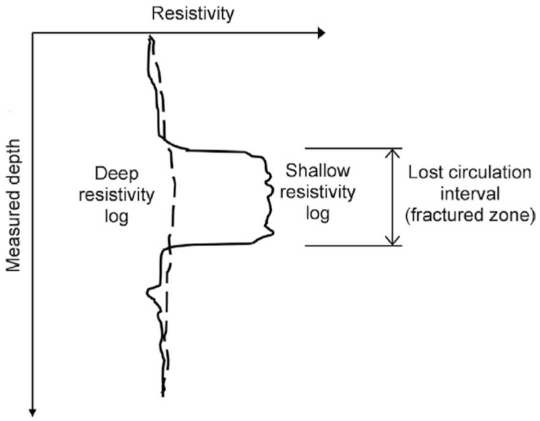

Fig. 5 Indication of short fracture

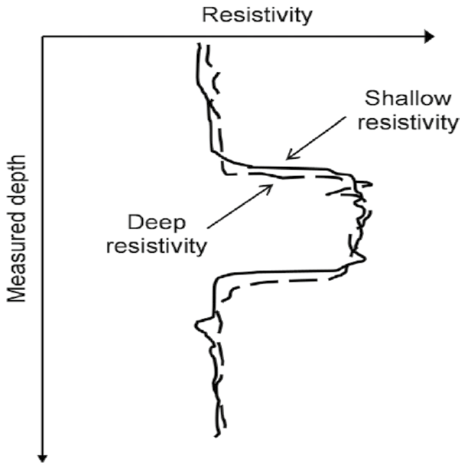

Fig. 6 Indication of long fracture [12]

6.3 Temperature Survey

Temperature logging is a helpful method to identify the thief zones. In geothermal wells, a temperature survey is commonly used to discover losses zones [2]. The profile of the temperature along an opened hole is logged after some hours of stopping the circulation. Then, when the circulation is resumed, the profile of the temperature is recorded again. The temperature discontinuities, which are the changes between the two profiles, point out where the drilling fluid goes during the circulation [13].

To improve the detection of lost circulation, the measurements of flow rate should be supported by additional data such as logging data, loss of circulation information (ECD, depth, duration), properties of the mud (rheology, mud density, particle size, solids content), and surface drilling parameters (torque, weight on bit (WOB), standpipe pressure, mud density, fracture gradient, and ROP).

7 Mitigation of Lost Circulation

Avoiding and mitigating lost circulation involves wide strategies and good preparation that should consider all the important factors during the operation. Loss of circulation can be mitigated by two approaches: preventive and corrective.

7.1 Preventive Approach

The preventive approach is based on managing the loss of return by planning ahead and possibly stopping its occurrence [51].

7.1.1 Controlling Bottom Hole Pressure

Applying a high overbalanced pressure could break the formation and cause losses. The wellbore pressure should be kept less than the fracture pressure and greater than the optimum formation pressure to prevent compressive failure of the rock [52]. The pressure can be controlled through minimizing the hydrostatic pressure in the wellbore using drilling fluid which has the minimum safe density [13] and minimizing the circulating density by changing the mud properties (yield point (YP), gel strength, and viscosity within the safe margin [53].

7.1.2 Wellbore Pressure Containment Improvement (WPCI)

Wellbore pressure containment is the highest pressure that wellbore can withstand which is higher than the lower in situ stress [54]. It is considered a major challenge in deep, HPHT wells. The circulation loss occurs in the formations of depleted sands, shales or leaking faults because of using a high mud weight [55]. To effectively manage the WPCI, the following information is required: last casing setting depth, casing size and properties, and drill pipe, rate of fluid loss, type and weight of drilling fluid and type of thief zone [56].

7.1.3 Running Intermediate Casing in the Transition Zones

The transition zone is the zone where the formation pressure is changed gradually from low pressure (normal formation pressure which is equal to 9 ppg) to high pressure. Most of the drilling problems including lost circulation occur in this zone because of the breakdown of the low-pressure formation when a high mud weight is used to drill this section. The problems coming from these zones can be prevented by protecting the formation using the intermediate casing [13].

7.1.4 Wellbore Strengthening

Wellbore strengthening enables the driller to use a high mud weight and make a very high overbalance (sometimes greater than 3000 psi) against a weak formation by plugging this formation using different plugging techniques [57]. The wellbore strengthening plugs are blends of different materials with different sizes that can penetrate the fractures and make a bridge to separate the wellbore from these fractures [36].

The preventive approach to mitigate the loss of circulation is easier than the corrective approach. Keeping the wellbore pressure equal to or very close to the formation pressure and avoiding the drilling through the thief zones (if possible) are the most efficient approach to prevent losses.

In some cases, preventive approach is not always effective, such as drilling in fractured and vuggy carbonate; therefore, corrective approach is required.

7.2 Corrective Approach

The corrective approach is the treatment that is applied only after the occurrence of lost circulation [7]. The treatment is done using different materials that defined as lost circulation material (LCM). When the thief zones are expected, the corrective approach includes the treatment of the drilling mud with loss of circulation materials (LCMs) that are usually blended with the drilling fluid to plug the loss zones when they are encountered [8].

LCM must have a perfect size selection to seal the fracture efficiently. If the size of the material is very large compared to the fracture size, they cannot enter the cracks or pores. In the same way, if the size of the material is very small, they cannot seal the fractures [10]. According to Kulkarni et al. [58], using large particles of LCM has two challenges. The first challenge that it can affect the rheology of the drilling mud and the equivalent circulating density (ECD). The second challenge is their tendency to settle out the mud.

7.2.1 Conventional LCM

It is important to understand and evaluate the behavior and the performance of LCM to prevent the loss of circulation. Howard et al. [28] classified LCM into four categories: dehydratable, lamellated, fibrous, and granular. White [9] added two types of LCM to the Howard's classification. He added flaky LCM and a mixture of LCMs. Nygaard et al. [59] increased the categories of LCM to seven; these are flaky, granular, fibrous, blended, water/acid-soluble, hydratable/swellable LCMs, and nanoparticles. Nygaard et al. [59] classification is based on the application, appearance and both the chemical and physical properties of the LCM. The chemical properties include the reactivity and swellability of the material with different chemicals and the solubility of these materials in acids. The physical properties contain the particle's size and shape [24]. In the following section, the plugging mechanisms of different LCM will be discussed and Table 2 summarizes the different properties and examples of LCM.

(A) Flaky LCM

A material can bridge and plug the thief formations. It has a large surface area and a flat and thin shape. Sometimes, it has no stiffness and can form a mat across the permeable zone [18, 28]. The examples of flaky materials are flaked calcium carbonate, mica, cellophane, vermiculite, and corncobs.

(B) Granular LCM

It is material that can pass through the pores and form a filter cake [60]. It can form a seal inside the pores of the formation or the fracture [18, 28]. It is rigid and has a high crushing resistance and stiffness which is suitable to seal the fracture and strength the wellbore by applying greater stress on the particles [7, 61]. Granulate materials are available in different sizes and lengths. The examples of granular materials are calcium carbonate, nutshells, gilsonite, graphite, asphalt, perlite, and course bentonite.

Table 2 Properties and examples of LCM

Lost circulation material (LCM)	Properties	Examples
Flaky	Large surface area Thin and flat shape No stiffness	Flaked calcium carbonate, mica, cellophane, vermiculite, and corncobs
Granular	Rigid High stiffness High crushing resistance	Calcium carbonate, nutshells, gilsonite, graphite, asphalt, perlite, and course bentonite
Fibrous	Long and slender shape Low stiffness	Sawdust, cellulose fibers, shredded paper, mineral fibers, and nylon fibers
Blended	Combination of different types	
Acid/water soluble	Not damaging the permeability Removable	Calcium carbonate, Magma fiber, ground marble and salts
Hydratable/swellable	Changeable in shape High elasticity	Polymer
Nanoparticles	Extremely fine and small	Iron hydroxide, calcium carbonate, and silica

(C) Fibrous LCM

A material is able to form a bridge across the formations pores to build a rapid mud cake [18, 28]. It is utilized commonly in vugular and fractured formations. It has low stiffness and long and slender shape [13]. It is less expensive and available in a wide range of particle size distribution. Fibrous materials include sawdust, cellulose fibers, shredded paper, mineral fibers, and nylon fibers. Some of the fibrous material is Magma fiber [62].

(D) Blended LCM

It is a mixture of two or more types of LCM. It can enter high-permeable vugs and fracture zones and plug them effectively. It has a significant effect on reducing the fluid loss compared to the individual LCM because of the various sizes and properties of the blended LCM [63]. Many studies focused on the efficient sealing of blended LCMs have concluded that the permeability of mud cake is minimized by using a combination of LCMs [33, 64].

(E) Water-/Acid-Soluble LCM

This material can be used in the reservoir section since it does not damage the formation's permeability because it is easily removable [65]. The development of these materials has increased compared to the conventional LCM (flaky, granular, fibrous and blended) which can damage the permeability of the reservoir [66]. Examples of water- or acid-soluble materials include calcium carbonate, Magma fiber, ground marble and salts.

(F) Hydratable/Swellable LCM

A material is changeable in shape. It is a mixture of different LCM with a highly reactive chemical additive such as a polymer which has a high elastic property. hydratable/swellable LCM is activated when it contacts the mud or the formation and seal the zone of losses [25].

(G) Nanoparticles LCM

They are extremely fine and small particles such as iron hydroxide, calcium carbonate, and silica. Nanoparticles can be prepared by two methods. The first method is by preparing a solution that contains the nanoparticles, and then later it was added to the mud. The second method is by directly preparing a drilling fluid with nanoparticles [67–70].

7.2.2 Other LCM

There are also different LCMs that have been used by many researchers to cure the losses zones such as cement plug, polyurethane grouting, settable plugs, cross-linked gel, and viscoelastic surfactant.

(A) Cement Plug

Cement is one of the most widely used LCMs. Many kinds of cement have been used as LCM. Different customized applications were developed using effective cement compositions and types. These applications differ based on the type and properties of drilling mud [71]. They contain ultrathixotropic and thixotropic cement slurries: slurries including calcium carbonate, flakes, and mica for mechanical bridging for control the loss [21]. It is not recommended to use the cement as a lost circulation material in the reservoir section because it cannot be easily removed. However, a new acid-soluble cement has been developed to be removed after lost circulation treatment. It provides good compressive strength and can be removed by hydrochloric acid, which reduces formation damage [72, 73].

(B) Polyurethane Grouting

Polyurethane grouting is a solution or a mixture of chemical grouts that react with each other and water to form a gel, leading to an increase in viscosity. Polyurethanes are one class of chemical groups which are pure resins solutions that are mixture of organic products in a solvent [71]. This group contains single element prepolymerized polyurethanes, which need water to start the reaction and two elements polyurethanes which are mixed and react together [74].

(C) Settable Plugs

A plug is utilized for slurry, which is a gel or solidified. Rigid setting fluids have been developed for sealing high circulation loss zones [75]. It is developed in a way that keeps fluid at low viscosity and reacts at certain bottom hole temperature [76]. It cannot be removed easily and difficult to spot in the correct zone [71].

(D) Cross-linked Gel

It is a high-viscosity gel formed by the development of cross-linked bonds between polymer chains [75]. This interior network might be the product of a chemical or physical cross-linking. Chemical gels include irreversible covalent bonds making the polymer network [77]. Adding more of these solutions to the mud formulations may rise the viscoelastic properties, improving the capability to sustain the temperature and pressure [75].

(E) Viscoelastic Surfactant

It is made of surfactants that self-assemble into worm-like micellar structures that act as polymers, raising the viscosity of the mud at low shear rates [78]. The worm-like micelle is damaged at a higher shear rate. However, when surfactant particles self-assemble added at small shear rates, worm-like micelle can be reformed which increases the mixture viscosity and enhances the pseudoplastic behavior.

8 Advantages and Disadvantages of LCM

Each type of the LCM mentioned above has some advantages and disadvantages [71]. Whatever LCM is utilized, it must be compatible with the drilling mud in the wellbore. It should have the ability to go through constrictions in the BHA. LCM should also have a slight impact on the permeability of the formation. Tables 3 and 4 show the advantages and limitations of each LCM.

9 Apparatus to Evaluate LCM

The evaluation of the LCM performance is conducted using different testing apparatus. The apparatus varies based on the capacity of the fluid loss at constant temperature and pressure [7, 61]. Some of these equipments vary based on the efficiency of LCM to seal fractured formations [63, 79–81]. The plugging efficiency of LCM depends on the size of the particles and the concentration of LCM. There are five common apparatus used to evaluate LCM such as particle plugging apparatus (PPA), LCM tester, impermeable and permeable fracture test, and HPHT fluid loss.

9.1 Particle Plugging Apparatus

It is a HPHT equipment that measures the filtration and bridging characteristic of the LCM. Ceramic disk and tapered slot are used by PPA as a filtration medium to simulate a fracture width ranging from 2 to 5 mm. To simulate the zones of fracture precisely, PPA has a various range of porosity and permeability. The apparatus's limitation is 500 °F (260 °C) for temperature and 5000 psi for pressure. When the test temperature is greater than 200 °F, backpressure should be applied to avoid fluid boiling. PPA has a hand pump, which applies hydraulic pressure to the cell. The size of the filtration cell is 300 ml. The filtration

Table 3 Advantages and disadvantages of main LCM

LCM	Advantages	Disadvantages
Granular	Form acid-soluble cake Resistant to surge and swap effects Non-compressible and granular	Brittle material Requires high solids loading Create formation damage due to Acidizing workover
Fibers	Removed without post-treatment Highly compressible and flexible Wide range of particle sizes High soluble in alkaline solutions Renewable, biodegradable, and inexpensive	Low acid solubility Shrinking and swelling Bacterial degradation Increase viscosity Affect pumping ability
Acid soluble	Available in a wide range of strength, density, and shape Compatible with other components of the fluid Non-damaging and non-toxic to the formation Reducing acid treatments Dissolve some solid particles	Degradable above 60 °C High manufacturing cost
Nanoparticles	Effective at plugging pore throats Thinner impermeable mud cake Control formation damage Reduce friction and wear	High manufacturing cost
Combinations of LCM	Works better in bridging fractures Reduce spurt losses Used in multiple applications	Affects density and rheology Cannot be dissolved by traditional treatments

Table 4 Advantages and disadvantages of other LCM

LCM	Advantages	Disadvantages
Cement plugs	Effective against severe and complete losses Permanent solution for the problem Can be used in reservoir sections	Applied in non-producing zones Irreversible process More expensive Delaying the drilling process
Settable plugs	No risk of bit nozzles plugging Cover a wide range of fracture widths	Hard to be set at the desired location Impacts on the environment
Cross-linked gels	High gel strengths Low cost	Damage the invaded zone Require removal treatment Form filter cakes after treatment Risk of premature or late gelation
Viscoelastic surfactants	Non-wall-building Obtained from renewable sources No need for remedial treatments Ability to break and recombine Fewer additives and easier to prepare Form gels at lower concentrations	Great dependence of viscosity with temperature Expensive low stability at temperatures higher than 200°F
Polyurethane grouting	Control setting time and viscosity Make a rigid plug Squeeze material into the loss zone Can be manufactured to be low viscosity	Hard to be set at the desired location Does not resist high-pressure differentials

Fig. 7 Particle plugging apparatus (PPA)

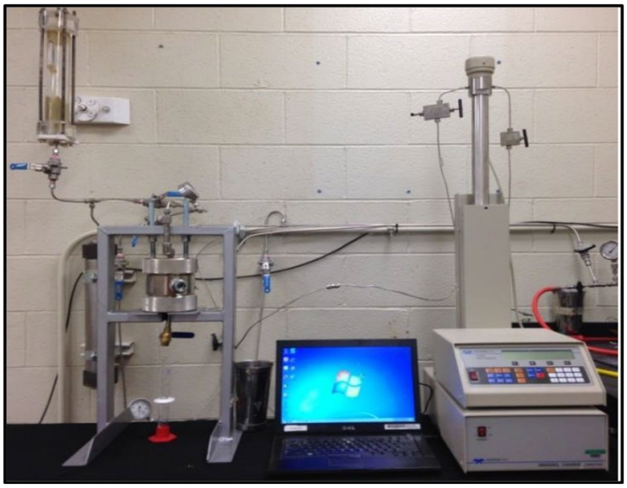

Fig. 8 LCM tester

is gathered out on the top to prevent wrong readings coming from settling of particles.

In addition, the modified PPA has been developed. It is high-pressure equipment that measures the filtration and bridging characteristic of LCM. Fabricated steel fractures are used as a filtration medium to simulate a fracture width that varies from 0.3 to 0.7 mm. The apparatus's limitation is a maximum pressure of 8700 psi. Figure 7 shows the PPA.

9.2 LCM Tester

It is a low-temperature low-pressure equipment used to evaluate the sealing efficiency of the LCM. Tapered slot and straight slot are used as a filtration medium to simulate a fracture width ranging from 1 to 5 mm for straight slot and from 2 to 12 mm for the tapered slot. The apparatus's limitation is 300 °F for temperature and 1000 psi for pressure. Figure 8 shows the LCM tester.

9.3 Impermeable and Permeable Fracture Testers

Impermeable fracture tester shown in Fig. 9 is a low-pressure equipment that measures the sealing efficiency of LCM. Uneven aluminum platens are used as a filtration medium to simulate a fracture width ranging from 0.3 to 1 mm. The apparatus's maximum pressure is 1250 psi. The apparatus has many components that enable the user of creating induced fractures horizontally or vertically using the treated drilling fluid. Permeable fracture tester (Fig. 9) is high-pressure equipment that measures the sealing efficiency of LCM. Porous plates are used as a filtration medium to simulate a fracture width that varies from 0.25 to 1 mm. The permeable fracture tester could be used for a maximum pressure of up to 6000 psi.

Fig. 9 Impermeable and permeable fracture tester

Fig. 10 HPHT fluid loss

9.4 High-Temperature High-Pressure Fluid Loss

It is a HPHT equipment used to measure the filtration characteristic of LCM. Filter paper and ceramic disk are used as a filtration medium to simulate a fracture width with different sizes. The apparatus's limitation is a maximum pressure that varies from 1500 to 2000 psi and maximum temperature that ranges between 350 and 500 °F. Figure 10 shows the HPHT fluid loss.

Table 5 summarizes all the apparatuses listed above with their specific limitations and details. When the formation is drilled, it is vital to consider the sizes of fractures. These fractures change as the pressure of the mud widens the current fracture or creates new fracture [82]. So, it is important to simulate the real cases of lost circulation in the laboratory. New modifications were conducted in the laboratory for testing the LCM. The HPHT cell was developed to be able to use different slot disks with different properties in order to simulate the actual cases of circulation loss as shown in Fig. 11a. Several disks varying in thickness and perforation size were modified to simulate the actual downhole bit nozzles in the cases of the circulation loss as shown in Fig. 11b, c. Also, different fracture geometry in slot disks (length, height, and width) was designed to simulate the most severe conditions of the losses as shown in Fig. 11d.

10 Prediction of Lost Circulation Using Artificial Intelligence

Loss of circulation is affected by many parameters related to formation characterization, drilling parameters, fluid properties, and a lot of other known and unknown factors, thus making it very hard to develop an analytical model to predict the losses or the zones of lost circulation. Therefore, many

Table 5 Apparatus used to evaluate LCM

Apparatus	Particle plugging apparatus (PPA)	LCM tester	Impermeable fracture test	HPHT fluid loss	Modified PPA	Permeable fracture test
Maximum temperature (°F)	500	300	–	350–500	–	~
Maximum pressure (psi)	4000–5000	1000	1250	1500–2000	8700	6000
Filtration medium	Ceramic disks API/ TS	API slots TS	Uneven aluminum platens	Filter paper ceramic disks	Fabricated steel fractures	Porous plates
Fracture width (mm)	2 mm (TS) 5 mm (SS)	1–5 mm (SS) 2–12.7 (TS)	0.3–1 mm	–	0.3–0.7 mm	0.25–1 mm
Measured values	Filtration/bridging	Sealing efficiency	Sealing efficiency	Filtration characteristic	Filtration/bridging characteristic	Sealing efficiency

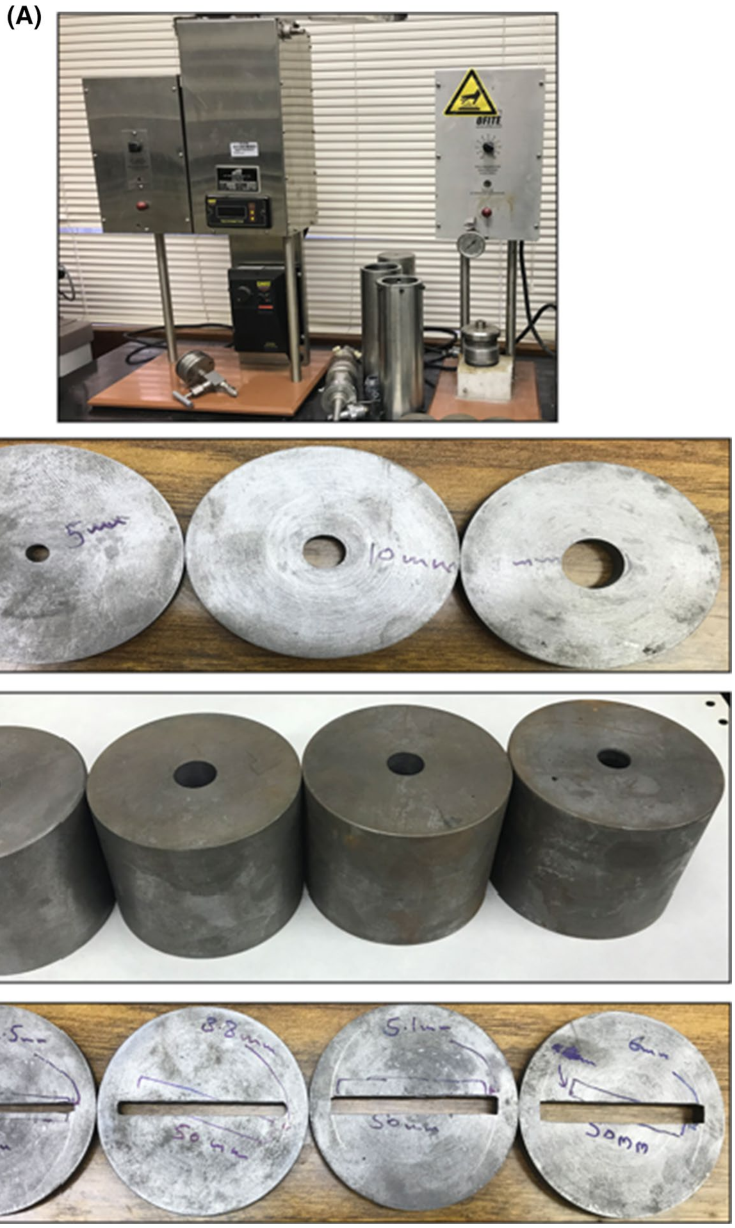

Fig. 11 Laboratorymodification

researchers tried to use artificial intelligence to predict the loss of circulation.

Moazzeni et al. [83] predicted the amount and existence of lost circulation using the artificial neural networks (ANNs). Data from 32 wells in Maroun oil field were used, and 18 parameters were used as inputs (current depth of the well from ground surface, current depth of the well from sea level, drilled depth, drilling time, open hole length, top of the formation, north direction of the well, east direction of the well, bit size, pump flow rate, pump pressure, mud density, solid percent, viscometer reading at 300 and 600 rpm, fluid loss, amount of losses in the day previous of losses problem, and amount of losses in 2 days previous of considered day). The data were divided into three parts (70% for training, 15% for testing, and 15% for validation). The ANN model estimated the rate of fluid loss with a correlation coefficient of 0.95 for training, 0.82 for the validation, and 0.77 for the testing data. It also estimated the type of losses with good accuracy.

Toreifi et al. [84] designed two models to estimate the lost circulation quantitatively and qualitatively in Maroun oil field using ANN. They used 1756 data point from 38 wells using 16 input parameters which are east and north coordinates, the current depth, formation tip depth, ROP, type of formation, annulus volume, pump pressure, mud pressure, flow rate, viscosity of filter cake, plastic viscosity (PV), YP, solid content, initial strength, and final strength after 10 min. 60% of the data were used for training, 20% for testing, and 20% for validating the developed model. The first model predicted the rate of losses with a high accuracy represented by a correlation coefficient of 0.95 for training and 0.94 for testing. The second model determined the type of losses (i.e., seepage, partial, severe, or total) with a correlation coefficient of 0.99 for training and 0.98 for testing.

Efendiyev et al. [85] studied the effect of petrophysical properties on the circulation loss. Fuzzy logic was used to determine the severity of the losses based only on two petrophysical properties which are permeability and porosity. They concluded that when the rock is impermeable and dense, the circulation loss is minor, when the rock is moderately permeable and low-porous, the circulation loss is intensive, when the rock is low-permeable and moderately porous, the circulation loss is partial, when the rock is highly permeable and porous, the circulation loss is catastrophic, and when the rock is permeable and highly porous, the circulation loss is serious.

Far and Hosseini et al. [86] studied the influences of depth, mud weight, flow rate, and pump pressure on lost circulation using ANN. They also used the ANN to predict the amount of the losses in Asmari formation. The data were divided into three parts: 70% to train the model, 15% for validation, and 15% to test the ANN model. The ANN model predicted the volume of losses with a correlation coefficient of 0.78 for the training, 0.98 for the validation, and 0.95 for the testing data.

Solomon et al. [87] used ANN to estimate the induced fracture's width and find the size of loss prevention materials. ANN model was trained and validated using an input data of 30 points. This resulted in a coefficient of determination of 79%. Predictability of the ANN model was compared with different fracture models, and the results indicated that ANN has an error of 15% compared to 26% error by other models.

Manshad et al. [88] applied support vector machine (SVM) to estimate the amount of lost circulation and radial basis function to predict the severity of the losses in Maroun oilfield. Three parameters from 30 wells were used as input parameters which are north and east direction, losses volume in the day before the day of study, and losses volume in 2 days before the day of study. SVM was able to estimate the quantity of the losses with a high performance of 79.6%. Also, the radial basis function was able to predict the quality of the losses with a high performance of 78.3%.

Al-Hameedi et al. [89] used machine learning to estimate the volume of lost circulation, in Dammam formation. Six input parameters from 500 wells were used in this study. These parameters are the ECD, mud weight, nozzles size (total flow area of the nozzles (TFA)), PV, ROP, and WOB. They were able to predict the volume of the losses with high accuracy in four different types of losses (seepage, partial, severe, and total).

Alkinani et al. [90] applied the ANN to predict the losses of drilling fluid in the induced fracture formation. They used mud weight, ECD, PV, YP, flow rate (Q), rotary speed, WOB, and TFA collected from 1500 wells as inputs. The data were divided into three parts: 60% for training, 20% for validation, and 20% for testing. Their ANN model predicted the loss of circulation with high coefficient of determination of 0.925.

Abbas et al. [91] implemented ANN and SVM to predict the occurrence of mud losses. A dataset of 1120 cases from 385 wells in a different field in Iraq was used in this study. The data have five types of losses (i.e., no losses, seepage losses, partial losses, severe losses, and total losses). The input parameters are lithology, MW, flow rate, ROP, circulating pressure, inclination, solids content, fluid loss, drillstring speed, WOB, YP, PV, Marsh funnel viscosity, 10-s gel strength, 10-min gel strength, azimuth, measured depth, and hole size. The data were divided into two parts: 75% to train the model and 25% to test the developed model. ANN predicted the losses with a correlation coefficient of 0.87 and 0.83 for training and testing data, respectively. SVM has the ability to predict the loss of circulation with high correlation coefficient of 0.92 for training and 0.91 for testing data.

11 Lesson Learnt

1. Loss of circulation is the most common, severe, costly, and time-consuming problem in oil and gas fields. The drilling fluid accounts for 25–40% of the total cost of the drilling operation, so any loss of the drilling fluid will significantly increase the total cost of the drilling operation. The loss rate depends on the drilling fluid types, and it is generally higher in the case of water-based drilling fluid than in the case of oil-based drilling fluid. Circulation loss costs 10–20% of the price of drilling an HPHT wells, and 90% of these losses occur in fractured formations.
2. The preventive approach to mitigate the loss of circulation is easier than the corrective approach. Keeping the wellbore pressure very close or equal to the formation pressure is the most efficient approach to prevent losses. It is very difficult to cure losses, especially in workover operations. The use of conventional LCM is not successful in all cases of lost circulation because of their limitations and disadvantages.
3. When the formation is drilled, it is vital to consider the size of fractures. These fractures change as the mud hydrostatic pressure increases which results in increase in the size of the existing fracture or creating a new fracture.
4. Loss of circulation is affected by many parameters that are related to formation characterization, drilling parameters, fluid properties, and a lot of other known and unknown factors, thus making it very hard to develop an analytical model to predict the losses or the zones of lost circulations.
5. Artificial intelligence (AI) is the one of the best techniques that can be used to predict the loss of circulation with a high accuracy in real time, but this technique required a record of huge data to train and test the AI models.

12 Recommendations

1. It is important to utilize an advanced measurement with high frequency to detect the occurrences of lost circulation quickly and correctly. To improve the detection of circulation loss, the measurements of flow rate should be supported by additional data such as logging data, loss circulation information (ECD, depth, duration), mud properties (rheology, mud density, particle size, solids content), and surface drilling parameters (torque, weight on bit, standpipe pressure, mud density, fracture gradient, and rate of penetration).
2. Whatever LCM is utilized, it must be consistent with the drilling mud in the wellbore, it should have the ability to go through constrictions in the bottom hole assembly, and LCM should also have a slight impact on the formation's permeability.
3. It is important to simulate the real cases of lost circulation in the laboratory using different slot disks with different properties and geometries. There is a need to develop the PPA instrument that can be used with real cores to evaluate the removal efficiency of the used LCM, especially in the reservoir section.
4. The implementation of AI in the drilling became more applicable. The AI is recommended to be applied in the issues of lost circulation because it can consider all the parameters that affect the losses in building the model and help the driller to prepare the treatment for this issue as quickly as possible. When the lost circulation is known, the driller can adjust the important drilling parameters to deal with the losses.

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