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Lost circulation and filter cake evolution: Impact of dynamic wellbore conditions and wellbore strengthening implications

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A B S T R A C T

Lost circulation events and mud filtration in drilling operations have been investigated over the years because they lead to non-drilling time (NDT) and increase the overall well cost. Solutions have been offered from the addition of fluid loss control additives, the use of lost circulation materials (LCM), advanced pills, to novel solutions and technologies such as wellbore strengthening, casing while drilling (CwD), and managed pressure drilling (MPD). However, lithology complexities, geothermal and geochemical effects, and wellbore drilling dynamics continue to push the boundaries to enhance available preventative and mitigation strategies.

In this study, pore and fracture-scale mud invasions are investigated and the results are used in characterizing filter cake wellbore strengthening. The methods used have been described in detail in the paper. The theoretical and experimental investigations revealed that wellbore temperature, drill string rotary speed, fracture width, rock permeability and porosity, LCM type, and LCM concentration are critical factors influencing filter cake evolution. SEM image and elemental maps of selected samples showed near-wellbore pore plugging by granular LCM. More than a 50% reduction in losses through a 2000 μm fracture width was recorded and concentration thresholds were established for the granular and fibrous LCM's, based on dynamic wellbore conditions. The numerical results showed that the rock permeability and filter cake permeability profiles largely control the changes in a wellbore hoop stress profile. This integrated approach will provide extensive details which will help inform decision making and select critical parameters for drilling different lithologies, loss prone zones, and achieving wellbore strengthening.

1. Introduction

Lost circulation can be defined as the loss of drilling fluid to the rock because of the differential pressure created by the equivalent circulating density (ECD) in overbalanced drilling operations. It is also referred to as mud/fluid loss or mud/fluid invasion. On the other hand, mud filtration occurs when drilling mud is filtered through the filter cake and rock pores, allowing only mud filtrate with ultra-fine particles to invade the rock. This process occurs concurrently with lost circulation and the severity of both problems depends on the porous media type, as well as other wellbore conditions and complexities. Although these mud loss categories (seepage, partial, and complete) provide a general idea of lost circulation intensity, the following mechanisms (vugs/carven, induced/natural fractures, and pore throats), suggested by Ghalambor et al. (2014), allows for developing effective preventative strategies. The primary goal of a preventative treatment is to reduce losses where natural fractures are anticipated and increase the fracture gradient by plugging drilling induced fractures and pore throats (Salehi and Nygaard, 2011; Majidi et al., 2011; Alberty, 2018). This is referred to as wellbore strengthening. To achieve this, it is important to review lost circulation field case events and highlight some important findings that can provide useful information on mitigation strategies. Ezeakacha (2014) conducted a comparative study and statistical review on several mud loss events and their mitigation approaches, culminated from several published reports and papers. Results from this study suggested that in one well, a mud loss interval can be up to 5000 ft and 48% of the case studies were between 100 ft and 1000 ft. Several parameters such as LCM concentration, mud formulation, type of rock, geothermal gradient, stand pipe pressure, flow rate, drill pipe/hole geometry, and drill pipe rotary speed were assessed and compared from well to well. The author concluded that up to 75% of the field cases had anticipated the losses which allowed for proper preventative planning for combating the challenge.

Considering a field scenario, operational conditions and pre-existing conditions are two broad groups of factors that can influence the intensity of mud and filtrate invasion (Ezeakacha and Salehi, 2018). As an

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important subject, mud loss and filter cake evolution have been discussed from the formation damage perspective (Civan, 2007; Chenevert and Dewan, 2001; Salimi and Andersen, 2004) and mud cake wellbore strengthening perspective (Ezeakacha et al., 2018a; Kiran and Salehi, 2016; Cook et al., 2016; Wang et al., 2016). Scanning electron microscope (SEM) image analysis of filter cake and other visualization techniques have provided qualitative characterizations of particle deposition and near-wellbore pore throat plugging (He and Hayatdavoudi, 2018; Ezeakacha et al., 2017; Fakhreldin, 2010; Al Otaibi et al., 2008; Byrne et al., 2000). The geomechanics and in-situ stress complications from mud loss and filter cake evolution have been highlighted by Feng and Grey (2018), Kiran and Salehi (2016), and Tran et al. (2011). All these approaches and perspectives share an interrelated goal, which is to improve drilling fluid design for mitigating formation damage while increasing the fracture graduate of the wellbore, based on the anticipated downhole conditions.

2. Experimental investigations

2.1. Experimental design and material selection

Drilling fluid design is a crucial factor to consider for mud cake wellbore strengthening. Water based mud (WBM) was selected over oil-based mud (OBM) because OBM's tend to prevent effective leak-off and have lower fracture propagation and reopening pressure compared to WBM (Morita et al., 1990). In this study, five water-based mud recipes were formulated with additives that are used in field operations. The first two recipes were formulated with two-single treatments of granular (coarse calcium carbonate) LCM. The granular LCM concentration was selected based on previous studies (Ezeakacha and Salehi, 2018; Ezeakacha et al., 2018b; Alsaba et al., 2014). Both recipes are shown in Table 1 and are considered the two levels for investigating mud cake wellbore strengthening in rock pores. The goal was to evaluate and quantify the pore throat plugging effect of coarse calcium carbonate using dynamic-radial mud invasion data, post experimental analyses, and a numerical approach. The last three recipes were three-single treatments (three different concentration levels of cedar fiber) of fibrous LCM shown in Table 2. The three-single treatment fluids of fibrous LCM were formulated to characterize mud invasion in a 2000 μm fracture width. The goal was to establish the wellbore strengthening limits of the mud cakes formed over the fracture width under dynamic wellbore conditions. Three concentrations of cedar fiber were chosen from both preliminary screening experiments and a past study (Alsaba et al., 2014). During the screening experiments, different LCM concentration recipes were tested. In all the recipes, barite was used as the weighting agent and the final slurry densities were between 10.96 lb/gal (ppg) to 11.05 lb/gabl (ppg).

The fluids in Tables 1 and 2 were designed based in mud invasion in rock pores and fractures respectively. The type of lithology, rock permeability, porosity, and mineralogical composition contributes to the complexity of mud invasion and formation strengthening. Five rocks representing five different lithologies were selected because of their underlying geochemical compositions, mineralogy, and complex pore networks. Fig. 1 shows some of the thick-walled cylindrical porous media with their properties and dimensions. Buff Berea sandstone was the fourth rock that was investigated. It is characterized with the same permeability as Michigan sandstone with 18.5% porosity. Both sandstones are composed of quartz and feldspar. Elemental maps reveal a high concentration of Aluminum and Silicon with some traces of Potassium and Zinc in Michigan sandstone. The pore throats of both sandstones are interconnected. While they may be prone to high mud invasion because of high permeability, they are potential candidates for mud cake wellbore strengthening. This is because a positive change in effective stress can occur when a permeable wellbore is exposed to a low-permeability mud cake (Salehi and Kiran, 2016). Upper Grey sandstone (105mD and 17.5% porosity) was the third sandstone that was investigated. Indiana limestone and Austin chalk are carbonate rocks that are primarily composed of calcite. Their pore structures and grains are influenced by chemical dissolution and recrystallization of fossil fragments. Indiana limestone grains can be crystalline or granular and they have strong calcite cementation. The pores of Indiana limestone are not often interconnected like most sandstone rocks. Austin chalk is a soft milky-white porous rock whose high porosity often compensates for its low permeability. It a depleted formation that lies above the Eagle Ford shale in Texas. Elemental maps for both carbonate rocks revealed the presence of Ytterbium (Yb) in addition to Calcium as the primary elements of the grains. Ytterbium is a rare earth element that is soft, ductile, and malleable. The concentration of this element in Austin chalk was much higher compared to Indiana limestone. This observation can partially explain the weak grain cementation in Austin chalk. The last figure to the right in Fig. 1 shows a custom-made 2000 μm fracture width slot. Previous studies have tested similar fracture width slots in a disk shape (AlAwad and Fattah, 2017; Wang et al., 2016; Alsaba et al., 2014). The advantage of using thick-walled cylindrical porous media is to account for pipe rotation and eccentricity which contributes to the mud cake plastering effect. All the dimensions in Fig. 1 are boundary constraints set by the core holder of the dynamic drilling simulator.

2.2. Experimental methods

The mud invasion experiments were conducted with a drilling simulator which has a maximum temperature and pressure limits of 500 °F and 2000psi respectively. The experiments were performed at 220 °F to determine the best performance of the fluids and filter cake evolution on the porous media at elevated temperature. Dynamic mud loss (pipe rotation only) was the response variable. For pressure, 100 psi differential was used for the experiments with core samples. Preliminary experiments showed that most of the rocks would break inside the core holder at higher differential pressures, rendering the experiments incomplete. This was attributed to their heterogeneity, composition, and possibly weak cementation of the rocks. Although, the Indian limestone samples were the only exception which is a testament to its strong calcite cementation, a differential pressure of 100 psi was

Table 1
Coarse calcium carbonate LCM treatments.

Fluid Additives	55 lb/bbl coarse calcium carbonate			80 lb/bbl coarse calcium carbonate		
	lb/bbl	% weight	% vol	lb/bbl	% weight	% vol
Water	296.51	64.10	84.72	292.15	63.20	83.47
API Bentonite	20.00	4.32	2.38	20.00	4.33	2.38
Caustic Soda	0.50	0.11	0.09	0.50	0.11	0.09
Lignite	4.00	0.86	0.76	4.00	0.87	0.76
Desco	4.00	0.86	0.71	4.00	0.87	0.71
Calcium carbonate	55.00	11.89	5.82	80.00	17.31	8.47
Barite	82.55	17.85	5.51	61.61	13.33	4.11