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Review of fundamental studies on lost circulation and wellbore strengthening

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A B S T R A C T

Lost circulation is one of the most common and costly problems in drilling operations, but in many operational situations, wellbore strengthening is an effective and economic technique to prevent or mitigate lost circulation. While numerous experimental and modeling studies have been carried out in the last three decades, there remain differing views regarding fundamental mechanisms of lost circulation and wellbore strengthening. An extensive and critical review of achievements and limitations on these fundamental studies is needed to aid engineers and researchers in future developments in this area. This paper provides a state-of-the-art review of fundamental studies on lost circulation and wellbore strengthening. This review focuses mainly on experimental and theoretical studies, rather than field experiences, intended to illustrate limitations of current knowledge in this area and lead to new research endeavors.

1. Introduction

Wellbore Strengthening, often shortened to WBS, has long been practiced in drilling operations to mitigate lost circulation, even prior to that specific identification. However, studies on fundamental mechanisms of wellbore strengthening became of widespread interest to the drilling industry with the DEA-13 (Drilling Engineers Association - 13) project (Morita et al., 1990). Carefully conducted experimental investigations on lost circulation were conducted, and remarkable enhancements in the pressure-bearing capacity of the wellbore due to wellbore strengthening treatments were observed in the DEA-13 project (Morita et al., 1990; Onyia, 1994). Since then, a number of experimental and modeling studies on lost circulation and wellbore strengthening have been published. It is generally accepted that most lost circulation events are caused by the extension of drilling-induced or natural fractures on the wellbore wall and that wellbore strengthening treatments can effectively mitigate lost circulation by increasing the fracture pressure (gradient) and widening the drilling mud weight window. However, the fundamental physics for the behavior of lost circulation fractures and how wellbore strengthening treatments work are still not fully understood. Different mechanisms and models have been reported in the literature without reaching a consensus (Arlanoglu et al., 2014).

This paper summarizes and organizes fundamental studies on lost circulation and wellbore strengthening published in the literature. State-of-the-art experimental and modeling studies are reviewed. The applicability and limitations of published works are compared and critiqued to clarify challenges and uncertainties encountered and to provide recommendations for future research in this area.

2. A brief background on lost circulation

2.1. Lost circulation and its consequences

Lost circulation (or lost returns) is the loss of partial or whole drilling mud into the formation while drilling a well. The drilling operation may continue when the loss rate is small and partial mud returns can be maintained. However, the operation stops when losses are too large or no mud returns are experienced (Wang, 2007). Lost circulation is a major cause of non-productive time (NPT) in drilling (Cook et al., 2011). Increased non-productive time can substantially increase operational costs, especially in deep-water drilling (Carpenter, 2014).

The mud level in the wellbore annulus may decrease when a large loss occurs. With reduced mud level, the bottom hole pressure may become insufficient to balance fluid pressure from the formation, resulting in the flow of formation fluid into the wellbore, i.e., a fluid kick. As a consequence, well control issues occur. These issues may include underground cross-flow/blowout (formation fluids flow from high-pressure zones to low-pressure or weak zones through the well-bore annulus) and surface blowout (formation fluids flow up to the ground surface) (Wang, 2007). Additionally, wellbore instability (col-

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lapse) may take place due to reduced annulus pressure caused by lost circulation. In some cases, the collapsed wellbore may result in buried drilling tools and stuck pipe (Lavrov, 2016; Messenger, 1981).

The above issues caused by lost circulation can significantly increase non-productive time and drilling cost. More than 12% of the non-productive time in shelf drilling in the Gulf of Mexico has been reported due to lost circulation (Wang et al., 2007a). The US Department of Energy reported that, on average, 10–20% of the cost of drilling high-pressure and high-temperature wells in the US is expended on lost circulation problems (Growcock et al., 2009). Worldwide, the impact of lost circulation on well construction is estimated at 2–4 billion dollars annually in lost productive time, lost drilling fluid, and materials used to stem the losses (Cook et al., 2011).

2.2. Lost circulation scenarios

Most mud losses are through hydraulic-driven fractures extending from the wellbore to the far field region (Feng et al., 2016). Lost circulation, therefore, will occur when the mud pressure in the wellbore is high enough to create new fractures or open pre-existing fractures on the wellbore wall. Lost circulation is mostly encountered in formations having a narrow mud weight window, the safe drilling margin between pore pressure (or collapse pressure) and fracture pressure.

Several typical scenarios with a narrow mud weight window are depleted zones, deep-water formations, naturally fractured formations, and deviated wellbores (Feng et al., 2016; Feng, 2016). In depleted zones, pore pressure reduction can lead to a remarkable decrease in the fracture pressure of the wellbore and thus a lower pressure-bearing capacity. In deep-water formations, considerable water depth can cause a lower-than-usual fracture pressure and result in a narrow mud weight window, making it very challenging to maintain needed wellbore pressure. Undesirable wellbore pressure fluctuations due to swab and surge can make things worse. In deviated wellbores, the mud weight window may diminish quickly with an increase in borehole inclination. This may even result in a zero window and an un-drillable well section. Pre-existing fractures in the formation can significantly affect the pressure-bearing capacity of the wellbore. A small fracture can lead to the loss of tensile strength of the wellbore rock and the fracture will propagate when the wellbore pressure overcomes the near-wellbore hoop stress only. If a large fracture is present, the maximum pressure a wellbore can withstand may reduce to the value of the minimum principal in-situ stress or pore pressure (Salehi, 2012).

It should be noted that lost circulation problems are also commonly encountered while drilling through carbonate formations which are often characterized by the presence of vugs and cavities (Davidson et al., 2000; Masi et al., 2011; Wang et al., 2010). However, lost circulation in carbonate formations is outside the scope of this review. The discussion herein is focused on lost circulation resulting from fracture extension in clastic formations such as sandstones and shales.

3. A brief background on wellbore strengthening

3.1. Definition and benefits of wellbore strengthening

Wellbore strengthening can be defined as the approaches used in drilling engineering to artificially increase the maximum pressure a wellbore can withstand without intolerable mud losses. In order words, wellbore strengthening seeks to enhance the effective fracture pressure and widen the mud weight window. Rather than actually increasing the strength of the wellbore rock as the name implies, wellbore strengthening is commonly believed to work by bridging, plugging, or sealing the fractures from which mud losses occur (Feng et al., 2016).

Besides preventing or mitigating lost circulation, wellbore strengthening techniques also have the potential for reducing associated non-productive time events, such as wellbore instability, pipe sticking, underground blowout, and kick. In some situations, wellbore strengthening can help reduce the required number of casing strings, thus reducing well construction costs.

3.2. Preventive and remedial wellbore strengthening

There are two kinds of wellbore strengthening treatments in the drilling industry, namely, preventive and remedial treatments. Simply put, preventive treatments attempt to “strengthen” the wellbore using lost circulation material (LCM) to prevent the creation of new fractures and extension of small pre-existing fractures on the wellbore wall before the lost circulation event. Remedial wellbore strengthening treatments attempt to “strengthen” the wellbore by bridging, plugging, or sealing the lost circulation fractures using LCM after a substantial loss has already occurred.

3.2.1. Preventive treatment

In a preventive wellbore strengthening treatment, LCM has a dual function. First, the LCM accelerates development of a filter cake on the wellbore wall. The filter cake usually has very low permeability and high ductility. It can help maintain a high fracture initiation pressure of the wellbore by effectively inhibiting pore pressure increase in the vicinity of the wellbore (Abousleiman et al., 2007; Tran et al., 2011). Second, the filter cake can quickly seal any pre-existing or drilling-induced micro fractures on the wellbore wall (Aadnøy and Belayneh, 2004; Cook et al., 2016). This prevents fluid flow into the fracture and pressure communication between the wellbore and fracture tip, thus increasing the required pressure for fracture propagation.

Preventive wellbore strengthening treatments based on plastering the wellbore wall with filter cakes have been widely used in the drilling industry and proven to be very effective, especially for lost circulation in depleted sandstone formations with relatively high permeability where filter cakes can form quickly.

Some experimental work reported in the literature has revealed the importance of the filter cake in inhibiting fracture growth and preventing lost circulation (Cook et al., 2016; Salehi et al., 2016; Salehi and Kiran, 2016). Field practices show that adding LCM additives to drilling mud to facilitate the development of filter cake can enhance the effective strength of the wellbore (Song and Rojas, 2006; Soroush et al., 2006; Sweatman et al., 2004). While some researchers insist that wellbore strengthening is achieved by bridging fractures at the wellbore to increase wellbore hoop stress (Alberty and McLean, 2004; Aston et al., 2004; Dupriest, 2005), other researchers maintain that similar wellbore strengthening results can arise by building a low-permeability mudcake on the wellbore wall to alter the effective stresses around the wellbore (Abousleiman et al., 2007; Feng, 2016; Tran et al., 2011).

It should be noted that development of filter cake is a time-dependent process not only because fluid leak-off from the wellbore is a transient process, but also because developments of the thickness and physical properties of the filter cake are functions of time (Bezemer and Havenaar, 1966; Chenevert and Dewan, 2001; Griffith and Osisanya, 1999; Jaffal et al., 2016; Sepehrnoori et al., 2005). These time-dependent processes can significantly affect the stress state around a wellbore (Tran et al., 2011). Properly characterizing the complex, time-dependent features of filter cake remains a challenging problem in the drilling industry.

3.2.2. Remedial treatment

A remedial wellbore strengthening treatment attempts to bridge, plug, or seal the fractures with LCM after drilling fluid loss has already occurred. The ultimate objective of remedial wellbore strengthening treatments is to arrest fracture propagation and increase the maximum pressure that a wellbore can sustain without further significant fluid loss. It is believed that the pressure-bearing capacity of the wellbore can be enhanced by one or a combination of the following mechanisms in a remedial treatment.