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The effect of wellbore circulation on building an LCM bridge at the fracture aperture

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ABSTRACT

Different laboratory experimental setups with slotted disks, simulating fractures' apertures, have been used extensively to formulate effective loss circulation materials (LCM) recipes. The amount of fluid loss and sealing pressure have been used as the evaluation criteria. The question still remains is how valuable these tests are when LCM fluids are circulated in the wellbore to stop losses. The main objective of this work is to study the effect of the annular fluid flow on building an LCM bridge at the fracture aperture.

To address the objective, a fluid loss apparatus has been developed to mimic wellbore circulation. Tapered slotted disks were placed upward in a cylinder filled with drilling fluid and LCM additives. Drilling fluid is pumped at the bottom of the cylinder and the wellbore circulation is simulated through the use of stirring paddle. Previously reported effective LCM recipes have been retested conventionally, no simulated circulation, and under simulated circulation condition (S_{circ}) with varying pump flow rates and tapered slotted disk sizes. A new term, sealing effectiveness ratio (SER), is introduced to effectively evaluate the sealing integrity of the LCM recipes at the S_{circ}.

The results showed when stirring the sample, a higher fluid loss was required before the sample sealed and the maximum sealing pressure (P_{max}) was lower than sealing pressures reported from conventional tests. Different LCM recipes required a different minimum flow rate for a seal to initiate at the S_{circ}. Increasing the flow rate improved the sealing effectiveness ratios of all LCM recipes. At high flow rates some recipes gave very similar P_{max} as conventional tests while others lost more than 35% of their strength. At a given flow rate with larger opening size slot, the effect of S_{circ} was amplified as higher fluid loss was required to initiate a seal and a lower sealing effectiveness ratio was recorded. The most significant new finding is that LCM with lower specific gravity was less prone to the S_{circ} making them better preventive approach candidates.

1. Introduction

As conventional reservoirs have been depleted, the oil industry start seeking deeper environments that are more challenging. These environments are associated with loss of circulation (LC) which costs the industry nearly a billion dollars a year (Al Menhali et al., 2014). LC is defined as losing some drilling mud into the formation, thief zone, and classified based on the LC severity, barrels per hour, as 1) seepage (<10 bbl/hr), 2) partial (10–50 bbl/hr), 3) severe (>50 bbl/hr), 4) total losses (no returns). However, this classification does not explain the mechanisms at which losses occur; resulting in inappropriate treatments. A classification based on the root cause was adopted later dividing losses into 1) pore throats, 2) induced or natural fractures, 3) vugs or caverns (Ghalambor et al., 2014).

Induced or natural fractures can be associated with partial to total losses depending on the amount of fluid overbalance (i.e. difference between mud weight and pore pressure) and the width of the fracture (Van Oort and Vargo, 2008). Curing this type of LC is often tied to enhancing the fracture gradient through a number of proposed mechanisms (Fuh et al., 1992; Alberty and McLean, 2004; Dupriest, 2005; Van Oort et al., 2009; Salehi and Nygaard, 2011a,b).

In an effort to identify effective conventional LCM treatments,

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Abbreviation: P_{max}, Maximum sealing Pressure; TS, Tapered Slotted Stainless Steel disk; GM, Ground marble; RG/ G, Resilient graphite/ graphite; CF, Cellulosic Fiber; NS, Nutshell; SCC, Sized Calcium Carbonate; $V_{initial}$, The volume at which the seal starts to develop; SER, Sealing Effectiveness Ratio; S_{circ}, Simulated Circulation Condition.

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straight slotted stainless steel disks (SS) and tapered slotted stainless steel disks (TS) have been used in different laboratory setups to simulate fractures' apertures. American Petroleum Institute published a recommended Practice (API Recommended Practice 13 B, 1974) to detail the testing procedures of the API slot tester device. TS were used in a Particle Plugging Apparatus (PPA) by Savari et al. (2014) and Kumar et al. (2011) where several successful combinations of LCM were formulated. The effects of varying LCM's type, size, concentration, temperature and other testing conditions for a range of TS sizes were also studied using the High Pressure LCM Test Apparatus (Al-saba et al., 2014a,b; Jeennakorn et al., 2017).

For an enhanced fracture aperture simulation, laboratory setups with two opposite plates were used. The plates permitted for a change in the slot width with the increase in the sealing pressure. The Impermeable Fracture Test Apparatus developed by Sanders et al. (2008) imitated fractures in impermeable rocks through the use of two aluminum plates. Permeable formations were simulated through two soapstone plates in an apparatus developed by Hettema et al. (2007). In these experiments, several effective blends of LCM were identified and a moderate correlation of spurt loss and sealing pressure was recorded.

The main objective of these laboratory tests was to formulate effective LCM recipes in an environment that simulates downhole conditions (i.e. permeability, temperature, pressure and fracture width & shape) to increase field success rate. However, some limitations and shortcomings were still associated with each setup, such as pressure limitation, LCM size limitation, settling concerns, and most importantly the effect of fluid movement along the wellbore, during circulation, on the LCM seal integrity. It is hypothesized that the crossflow along the fracture aperture caused by the circulation of drilling fluid during drilling operations is reducing the LCM ability to form a bridge. The main objective of this work is to study the effects of wellbore circulation on building an LCM bridge at the fracture aperture.

2. Experimental setup

To introduce a simulated circulation condition (S_{circ}), a crossflow along the fracture aperture, and evaluate LCM recipes at high pressure, a commercially available stirred fluid loss tester (M7150 Stirred Fluid Loss Tester, 2017) has been chosen as a base of the build. Several changes were made on the tester to prepare for LCM S_{circ} testing. A new cell was fabricated to handle LCM mud, fit the tapered slotted disks, and ensure a thoroughly mixing of the LCM mud by positioning the disks closer to the paddle tip (Fig. 1).

The simultaneous stirring action and fluid injection along with fluid loss and seal integrity measurements were accomplished by incorporating the modified fluid loss cell (Fig. 1) with a flow apparatus shown in Fig. 2.

In this setup, drilling mud was used instead of nitrogen gas as an injection fluid to mitigate any channeling or gas migration concerns; since pumping is performed upwards opposed to gravity. The tester is designed to provide either constant flow or constant pressure, 0–1000 psi, modes achieved by syringe pump (1) and a bladder accumulator (2) combined with a pressure regulator (3) respectively. The pressure is recorded electronically at two points, the syringe pump and the pressure transducer (4). The syringe pump and the regulator are protected from any corrosive fluid and any plugging concerns are avoided by using a floating piston accumulator (5). The accumulator provides the means of separating the two fluids, mud & distilled water, and transferring the pressure. A plastic accumulator (6) is used as a mud refilling reservoir if needed.

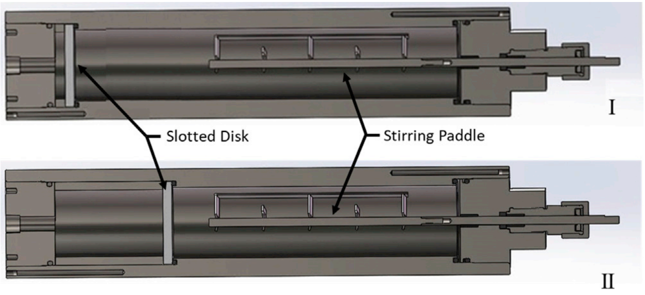

Fig. 1. I. Factory testing cell. II. New fabricated testing cell.

3. Methodology

In this set of experiments, effective LCM formulations with proper concentration and particle size distribution (PSD), to seal a given fracture width, have been chosen from a previous reported study (Al-saba et al., 2014a,b). The formulations consisted of graphite (G), sized calcium carbonate (SCC), nutshell (NS) and cellulosic fiber (CF). Table 1 illustrates the formulations and PSD.

The study used two sizes of tapered stainless steel disks, TS1 and TS4, which were manufactured locally in accordance to Al-saba et al., (2014a, b) disks' specifications. Fig. 3 shows a schematic of the TS. The two disks have dimensions of 2.5″ in diameter and 0.25" in thickness. The opening widths of fracture aperture and tip of TS1 were 2500 and 1000 microns respectively while they were 5000 and 2000 microns for the larger disk (TS4).

The LCM formulations were re-tested conventionally, no S_{circ}, at 25 ml/min flow rate to establish a baseline for the subsequent S_{circ} tests. The tests were conducted at various flow rates ranging from 10 ml/min to 175 ml/min magnifying the S_{circ} effects.

Formulating drilling fluid with an accepted carrying capacity, to prevent LCM settling, under the S_{circ} was a challenge. Since most drilling fluids are non-Newtonian, their viscosity and carrying capacity decrease with the increase in shear rate. According to Baldino et al. (2015) "At medium and high shear rates the dynamic viscosity of drilling fluids decreases considerably and the effect of yield stress is no longer present". Moreover, the work done by Murphy et al. (2006) indicated that under a dynamic condition gel strength can't build fast enough to support particle suspension. The other observed downside of stirring action was getting LCM pushed towards the wall of the cell causing them to settle much quicker than the one in the center; which is in correspondence to the observations by Fang (1992).

To overcome these problems Hydroxyethyl Cellulose (HEC) was added to 7% by weight bentonite mud, Mud 1. The HEC contributed towards adding more pseduoplasticity to the fluid resulting in a higher velocity gradient in the center of the flow stream with more viscous stagnant fluid at the wall (Powell et al., 1991). HEC fluid also exhibits higher shear stress with the increase in shear rate. The combination of both characteristics of HEC dramatically improved settling issues. A 15.4 ppg barite weighted bentonite mud, Mud 2, was also found to be effective with an improved fluid carrying capacity with zero settling rate under a static condition. Table 2 illustrates the formulations and rheology of both muds.

To test the carrying capacity of Mud 1 and Mud 2 under the S_{circ}, a fixed volume of LCM mud was collected repeatedly starting at the bottom of the cell after 20 min of stirring. The LCM were screened from the mud, left to dry, and then weighted up. Table 3 shows the percentage of particle distribution along the height of cell.

Table 3 indicates that the HEC bentonite mud (Mud 1 Table 2) or the weighted bentonite mud (Mud 2 Table 2) prevents settling for the duration of testing and thus those two mud formulations were used for the study. The procedure for all tests was to fill the cell with LCM mud to the tip of paddle, while the space above the paddle and towards the cell end cap was filled up with LCM free mud to ensure adequate stirring of LCM and prevent sealing before flow was initiated.