Article

Novel Cake Washer for Removing Oil-Based Calcium Carbonate Filter Cake in Horizontal Wells

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Abstract: An impermeable layer “filter cake” usually forms during the overbalanced drilling technique. Even though it helps in protecting the formation from a further invasion of drilling fluids, the removal of this layer is essential for a proper cement job and to avoid any reduction in wellbore deliverability. The design of the removal process is complicated and depends on the filter cake composition and homogeneity. This paper presents an experimental evaluation on the usage of a novel cake washer (NCW) in the removal of a filter cake formed by an invert emulsion oil-based drilling fluid that contains calcium carbonate as a weighting material while drilling a horizontal reservoir. The proposed NCW is a mixture of organic acid, mutual solvent and nonionic surfactant. It is designed to enable restored wellbore permeability for a sustainable production. Since the filter cake mainly consists of the weighting material, the solubility of calcium carbonate in NCW at different ranges of temperature, duration and concentration was investigated. An actual casing joint was used to test the corrosion possibility of the treating solution. High-pressure and high-temperature (HPHT) filtration tests on ceramic discs and Berea sandstone core samples were conducted to measure the efficiency of the filter cake removal and the retained permeability. Ethylene glycol mono butyl ether (EGMBE) was used as a mutual solvent and the solubility was higher compared to when the mutual solvent was not used in the washer formulation. A significant increase in calcium carbonate dissolution with time was observed for a duration of 24 h. The solubility was found to be proportional to the concentration of NCW with optimum results of 99% removal at a temperature of around 212 °F. At those conditions, no major corrosion problems were detected. Permeability of the core retained its pristine value after the treatment.

Keywords: calcium carbonate; filter cake; oil-based mud; cake washer; retained permeability

1. Introduction

The drilling fluids have many operational objectives, such as drillstring and drill bit lubrication [1], cuttings lifting and suspension [2], the prevention of formation fluids invasion, and the creation of a thin filter cake that protects formations from being contaminated by the drilling fluid additives [3–5].

Due to a pressure difference between the formation and the wellbore during overbalanced drilling, fluid particles tend to invade the near-wellbore vicinity which could result in the rock plugging, and hence, permeability reduction [6]. This invasion is significantly reduced when a thin impermeable layer called a filter cake is built at the surfaces of the wellbore [7]. The filter cake is an impermeable, thin layer with a permeability range from 0.0001 to 0.01 mD [8,9]. Despite its vital role during drilling, the filter cake must be removed afterwards for a better cementing job and to avoid any reduction in hydrocarbon production [10,11].
Weighting additives are added to the drilling fluids to obtain the desired density to ensure a proper hydrostatic pressure in the well [12]. These weighting additives have a considerable effect on the created filter cake structure as they composed 70 to 80 wt% of the formed filter cake [13–16]. Therefore, the efficiency of filter cake removal depends mainly on the solubility of the weighting material in the chemical solution. Elkatatny et al. studied filter cakes and reported that filter cakes consist of two layers, one containing the polymer (away from the formation) and the other layer contains the solid particles closer to the rock surface [17–19]. The drilling fluid’s components and additives considerably affect the filter cake’s structure and its characteristics [20,21]. Various chemical solutions (oxidizers, enzymes, acids and acid precursor) are available as solvents for the calcium carbonate contained in the filter cake [22–24].

The recent advances in nanotechnologies’ applications in the oil and gas industries have allowed for the development of nanoparticle-based drilling fluids with enhanced properties. Several experimental evaluations on the nanoparticle drilling fluids demonstrate the enhancements in rheological properties, thermal stability, lubrication, hole cleaning and shale stability. Additionally, there can be fewer filtration losses and thinner and more compact filter cakes compared to the conventional drilling fluids [25–29]. Although improvement by nanotechnology can decrease the thickness of the mud cake, its removal is still an issue.

When drilling shaly sands, oil-based drilling fluid (OBDF) is considered a better option than water-based drilling fluid (WBDF). The former shows better stability and fewer swelling issues over the latter. In addition, OBDF has stable rheology, less filtration and better hole cleaning than WBDF [30–32], and is often used in completing the pay-zone section [33]. However, the oil presence in OBDF complicates the filter cake removal processes. Due to its chemical nature, oil tends to coat the weighting materials and act as a dissolution inhibitor during the cleaning stages [34,35]. Hence, a wettability alteration of the oil-weighting additives-water system is needed prior to treatment [36].

The removal process of filter cakes is challenging and requires several considerations, such as filter cake homogeneity, particle size distribution, formation characteristics, drilling fluid type and additives [12,37]. Price-Smith et al. carried out an acid dissolution of filter cake study and showed that live acids cannot uniformly remove heterogeneous filter cakes [38]. Moreover, solid particles in the filter cake can be coated with polymers, which act as a barrier reducing acid contact with the filter cake [39].

Much effort has been made for oil-based filter cake removal. Leschi et al. and Al-Kuaiti et al. proposed the use of organic acid precursor (OAP) and water wetting additives [40,41]. Micro-emulsion solutions formulated from alcohol and surfactants have been suggested [42–44]. Another approach utilizing an oxidant agent (persulfate salt) and a non-ionic surfactant has also shown some improvement in filter cake removal [45].

Quintero et al. [46] investigated the use of micro-emulsion on OBDFs’ filter cake removal. The investigated single-phase micro-emulsion (SPME) consists of water, solvent and surfactant diluted in calcium chloride brine. Soaking the filter cake in SPME altered the wettability of the filter cake and resulted in more porous and loosely consolidated filter cake, even without acid addition. Several retained permeability tests were conducted to evaluate the performance of SPME combined with hydrochloric acid or acetic acid, on removing the filter cake generated by invert emulsion drilling fluids with calcium carbonate, barite or a mixture of calcium carbonate and barite as the weighting material, over a ceramic disc or sandstone core. SPME mixtures with hydrochloric acid or acetic acid were able to restore the permeability after the drilling fluid damage.

In situ acid generation by acid precursors is one of the techniques in filter cake removal that delay the acids/filter cake particles reaction, resulting in a more even reaction rate over the treatment section. Binmoqbil et al. [47] studied a combination of a formic acid precursor and surfactant for OBDFs’ CaCO₃ filter cake cleanup. CaCO₃ solubility in the formic acid precursor was measured over time and temperature, which reflects the acid’s strength and generation rate. The acid generation rate was higher at 188 °F compared to the room temperature, which means a shorter delay period at
reservoir conditions. Two high-pressure and high-temperature (HPHT) removal tests were conducted at different surfactant concentrations: 2 and 4 vol.%. In both tests, the filter cake was efficiently removed and the permeability restored, and there was no significant difference between the results of the two surfactant concentrations.

Mohamed et al. [34] presented a washer that consists of a biodegradable acid and a mutual solvent diluted by water. HPHT removal efficiency and retained permeability tests on sandstone and limestone cores were conducted, along with a corrosion test to evaluate their new cleaning fluid. The new biodegradable acid system (NBAS) was able to remove the filter cake and restore the permeability with an acceptable corrosion rate. This solution is recommended for vertical wells where the time required for fluid distribution is small as the reservoir section in the vertical well is small.

Although there are many suggested solutions for oil-based filter cake removal, there is a need to develop a new solution which can be used over a wide range of temperatures to remove the oil-based filter cake in the long horizontal section. The developed solution should have a slow reaction rate, a very low corrosion rate, and will not require corrosion inhibitors and intensifiers which usually alternate the formation wettability.

The objective of this study is to develop a new cake washer that can be used at a wide range of temperatures to remove the oil-based filter cake in horizontal wells with high efficiency and a low corrosion rate. In this paper, a laboratory evaluation on a novel filter cake removal is presented. The procedure followed for the treatment design includes a solubility test for calcium carbonate particles in a novel cake washer (NCW) at different conditions, such as duration, temperature and acid concentration, a corrosion test of the actual casing joint at HPHT, and filter cake removal efficiency at 212 °F and 300 psi, and retained permeability on a ceramic disc and Berea sandstone core sample. NCW removal performance was compared with different studies that investigated removal solutions for filter cakes generated by OBDF with calcium carbonate as a weighted material [34,46,47]. The comparison against the presented study was conducted based on the filter cake removal efficiency, the retained permeability and the corrosion rate generated by the cleaning fluid, as possible.

2. Materials and Methods

The experimental work started with various solubility tests in which a magnetic stirrer with a condenser was used to measure CaCO₃ solubility in NCW for different time durations, NCW concentrations and some ranges of temperature. After testing the effectiveness of NCW in CaCO₃ dissolution, HPHT corrosion tests were performed using an actual casing joint for 6 h without using corrosion inhibitors at 212 °F.

A HPHT filter press was used to build a filter cake over 2.5 inches of Berea sandstone core and a ceramic disc at 212 °F and 300 psi differential pressure. Then, in the same cell and at the same conditions, the core with the formed filter cake was soaked with NCW for 24 h to check for the removal efficiency. In order to check the effect of the cake washer on restoring the rock permeability, the permeability of the core sample was measured after the removal test and compared against its pristine value.

2.1. Oil-Based Mud

Actual field invert emulsion drilling fluid extracted from a flow line was used in this experimental study, the OBDF consisted of diesel and water as the continuous and dispersed phases, respectively. Two different particle-size-distributions of calcium carbonate CaCO₃ were used as bridging and weighting materials, fine (D₅₀ = 25 microns) and medium (D₅₀ = 50 microns). The other OBDF components included a bridging agent, viscosifier, a filtration control material, and primary and secondary emulsifiers. Table 1 lists the formula of the drilling fluid used in this study. The fluid had a density of 79 lb/ft³, an oil/water ratio of 81/19 and 38.8 wt.% total solid content.
Table 1. Oil-based drilling fluid formulation.

| Additive              | Amount | Unit | Task                  |
|-----------------------|--------|------|-----------------------|
| Diesel                | 0.59   | bbl  | Continuous phase      |
| Invermul              | 1      | gal  | Emulsifier            |
| Lime                  | 4      | lb   | Alkalinity            |
| Versalig              | 6      | lb   | Filtration control    |
| Fresh water           | 0.16   | bbl  | Dispersed phase       |
| VG 69                 | 6      | lb   | Viscosifier           |
| Ezmul                 | 0.5    | gal  | Emulsifier            |
| CaCl$_2$              | 33     | lb   | Salt                  |
| Fine CaCO$_3$ ($D_{50}$ = 25 microns) | 140 | lb | Weighting material  |
| Medium CaCO$_3$ ($D_{50}$ = 50 microns) | 20 | lb | Bridging material  |

The drilling fluid’s rheological properties were tested at 120 °F, as shown in Figure 1. The plastic viscosity was 18.9 cP and the yield point was found to be 16.7 lb/100 ft$^2$.

![Figure 1. Shear rate vs. shear stress at 120 °F.](image)

2.2. Cleaning Fluid

The investigated novel cake washer was a mixture of the following chemicals:

- Acetic acid (15 wt%): an organic acid that is less corrosive than hydrochloric acid (HCl) especially at high-temperatures, and is compatible with formations that contain HCl sensitive clays.
- Mutual Solvent (15 wt%): an additive for stimulation treatments that is soluble in oil, water and acid-based treatment fluids. The mutual solvent used in this cake washer formula was ethylene glycol mono butyl ether (EGMBE). The purpose of the mutual solvent is to remove the oil that covers the surface of the CaCO$_3$ particles in the filter cake and thus allowing the acid/solids interaction to happen.
- Nonionic surfactant (3 wt%): to change the wettability of filter cake from oil to water wet.
- Distilled water: as the continuous phase.

NCW had a pH of 2.7, 1.02 specific gravity, 24 mN/m surface tension, and a viscosity of 2.11 cP all measured at room temperature and atmospheric pressure.

2.3. Core Sample

A ceramic disc and a Berea sandstone core sample were used as the porous medium for filtration and the filter cake removal tests. The core was 2.5 inches in diameter and 1.07 inches in height, and had a diesel permeability of 98.6 mD. A 50-micron ceramic disc (2.5 inches in diameter and 0.25 inches
in thickness) with a permeability of around 15 Darcy was used. Both materials were originally dried and saturated totally by diesel before the experimental work.

3. Results and Discussion

3.1. Mutual Solvent Effect

The cake washer was originally prepared without the mutual solvent. The solubility tests were made at 212 °F. Then, the mutual agent was added and the solubility tests were carried out again. The solubility increased from 73 to 83 g/L when the mutual agent was added. This can be attributed to the fact that the mutual solvent in the formulation acted as a retarder to the reactive part and delayed the reaction. That retardation allowed for more dissolution. Based on this observation, the mutual solvent was kept in the NCW formulation for any further tests.

3.2. Solubility Duration

CaCO₃ solubility in NCW for different durations was conducted at 212 °F. As shown in Figure 2, there are no significant increases in CaCO₃ solubility after a 24 h period. The duration of any subsequent treatment was planned accordingly.

![Figure 2. Calcium carbonate solubility with time at 212 °F.](image)

3.3. NCW Concentration

To assess the effect of the NCW concentration on solubility, two different mixtures diluted with deionized water were prepared. In particular, 50 and 75 vol.% of the washing solution were prepared and the solubility was determined at 212 °F. Figure 3 shows that the maximum solubility was obtained when no further dilution was made. This was due to the reduction of the acid concentration that yielded less solubility. Therefore, 100% of NCW is to be used in subsequent treatments.
3.4. Temperature

Figure 4 shows the CaCO₃ solubility over a wide range of temperatures. It could be observed that the maximum solubility was achieved at 212 °F, where around 83 g/L of calcium carbonate was dissolved. Further increase in the temperature resulted in decreasing the solubility. This could be due to a reduction in the retardation effect by the mutual solvent. Consequently, the solubility of the whole formulation decreased.

3.5. Corrosion Test

An actual casing joint was used in the corrosion test. NCW of 2.7 pH was tested for its corrosion effect at 212 °F and 1000 psi. The corrosion rate after 6 h was found to be 0.000268 lbm/ft², which indicates minimal corrosion problems. This could be compared to the corrosion by the hydrochloric acid, which was 0.65 lbm/ft² at the same conditions and the accepted corrosion rate of 0.05 lb/ft² at this temperature.
3.6. Filter Cake Removal

An HPHT filter press was used to build the filter cake on a ceramic disc, and again on a 2.5 inch Berea sandstone core for 30 min at 212 °F and 300 psi. Figure 5 illustrates the filtration over time, it is noticeable that in both materials the fluid generated the filter cake within 30 min and the total filtration volumes were relatively small and less than 2.5 cubic centimeters. Figure 6 shows the generated filter cake on the core and the ceramic disc. The thickness of the filter cake was 1.2 mm and 1.5 mm on the ceramic disc and the core, respectively.

![Figure 5. Cumulative filtrate volume over time.](image)

![Figure 6. Generated filter cake on (a) the ceramic disc and (b) the sandstone core.](image)

The core/ceramic disc with formed filter cakes were soaked into 250 cm³ of the investigated solution in a HPHT filter cell at 212 and 300 °F for 24 h. Figure 7 shows post-treatment images of the core and the ceramic disc. The effect of the NCW soaking on the filter cakes was obvious, as shown in Figure 7, and can be quantified by calculating the removal efficiencies using the following formula:

\[
\text{Removal Efficiency} = \frac{W_2-W_3}{W_2-W_1} \times 100\% \tag{1}
\]

where

- \( W_1 = \) weight of the diesel saturated core/disc, g
$W_2$ = weight of the filter cake containing core/disc, g
$W_3$ = core/disc weight after the removal process, g

![Figure 7. (a) The ceramic disc and (b) the core after 24 h soaking into NCW.](image)

The efficiency for both cases was found to be more than 99%. Furthermore, the diesel permeability was remeasured and the permeability of the sandstone core was 100% of the original permeability.

### 3.7. Results Comparison with Similar Studies

In order to evaluate the NCW removal performance, the results were compared with three different studies that investigated removal solutions of filter cakes generated by oil-based mud with calcium carbonate as a weighting material, [46,47,34]. Table 2 shows the filter cake removal efficiency, the retained permeability on sandstone cores, and the corrosion generated by the cleaning fluid for the aforementioned studies and for the proposed one. The retained permeability and weight removal efficiency percentages resulting from the use of the NCW were around the same values as the other procedures. Some of the selected studies did not present the removal efficiency or the corrosion rate. Even though Mohamed et al.’s [34] results have an acceptable range of corrosion rates, NCW showed a lower corrosion rate, (note that both tests conducted at 212 °F for 6 h contact). All of the results presented in Table 2 were conducted on sandstone cores for the sake of consistency. According to the results presented in this table, it can be concluded that NCW showed promising results on all of the selected three performance criteria.

### Table 2. Comparison of different filter cake treatments where calcium carbonate is used as the oil-based drilling fluid (OBDF) weighting material. All reported procedures were conducted on sandstone cores.

| Author       | Removal Solution                                      | Removal Efficiency | Retained Permeability Percentage | Corrosion       |
|--------------|-------------------------------------------------------|--------------------|---------------------------------|-----------------|
| Quintero et al. [46] | Micro-emulsion (water, solvent, surfactant, co-surfactant) + acetic acid (16 h) | NA                 | 85.3–100.3%                    | NA              |
| Binmoqbil et al. [47] | Formic acid precursor + surfactant (24 h)            | NA                 | 100.4%                         | NA              |
| Mohamed et al. [34] | Biodegradable acid + mutual solvent + water (24 h)    | 100%               | 100%                           | 0.03 lb/ft²     |
| Current study     | NCW (24 h)                                            | 99%                | 100%                           | 0.000268 lb/ft² |
4. Conclusions

A novel cake washer was investigated for the removal of filter cake generated from an invert emulsion drilling fluid with calcium carbonate as a weighting material. Based on the obtained results, the following conclusion can be drawn:

- The detected corrosion rate was relatively low (0.000268 lbm/ft²) after 6 hrs of testing at 212 ºF, which is far below the accepted corrosion rate of 0.05 lb/ft² at this temperature.
- CaCO₃ solubility was significantly decreased when the solution mixture was further diluted with water.
- The highest dissolution rate was achieved at 212 ºF.
- No increase in solubility was achieved after a 24 h duration.
- The removal efficiency obtained using the novel washer on the ceramic disc and the sandstone core sample was more than 99%, with 100% restored permeability for the latter.
- The comparison between NCW and other solutions in similar conditions showed close results in terms of retained permeability, yet NCW had a lower corrosion rate.

5. SI Metric Conversion Factors:

| Unit       | Conversion Factor |
|------------|------------------|
| 1 micron   | $1 \times 10^{-6}$ m |
| 1 mm       | $1 \times 10^{-3}$ m |
| 1 inch     | 0.0254 m         |
| 1 Darcy    | $9.869233 \times 10^{-13}$ m² |
| 1 bbl      | 0.158987294928 m³ |
| 1 gal      | 0.00378541 m³    |
| 1 lb       | 0.453592 kg      |
| 1 g/L      | 1 kg/m³          |
| 1 lb/ft³   | 16.0185 kg/m³    |
| 1 psi      | 6894.76 Pa       |
| 1 lb/ft²   | 47.88 Pa         |
| 1 cP       | 0.001 Pa.s       |

$$T(\text{°C}) = \frac{T(\text{°F}) - 32}{9} \times \frac{5}{9} - 459.67$$

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