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## Cleanup characteristics and mechanisms of reversible invert emulsion drilling fluid

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## ABSTRACT

Reversible invert emulsion muds (RIEMs) offer unique advantages over other oil-based muds for the completion of a well due to the pH-responsiveness of reversible emulsifiers. This paper presents new insights into the effects of pH-responsiveness on the completion performance of RIEMs and the mechanisms involved.

At pH 4 and 6, RIEMs are easy to remove, but the formation damage is relatively severe. At pH 10, the removal of RIEMs is relatively difficult but can be facilitated by intense and repeated flushes. Once the mud has been removed, there is little formation damage. At pH 8, the mud is very difficult to remove, and the greatest amount of formation damage is observed.

The spontaneous curvature of the surfactant layer changes at pH 4 and 6, resulting in the emulsion inversion and thereby enabling the removal of RIEMs by the solvent effect. These changes do not occur at pH 8 and 10. More emulsifiers adsorb to the rock surface at pH 4, 6, and 8, resulting in a strongly oil-wet condition and high formation damage. The desorption of emulsifiers occurs at pH 10, causing a water-wet condition and low formation damage. The variety in chemical states accounts for the changes in the adsorption behavior of the emulsifiers.

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## 1. Introduction

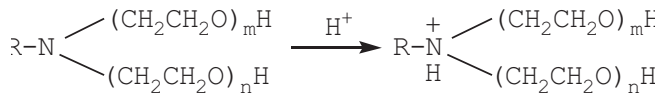
Conventional oil-based drilling fluids are typically designed for high emulsion stability and strong oil-wetting characteristics, which are beneficial to the drilling operation in that they produce superior wellbore stability, excellent lubrication and an enhanced rate of penetration (Chambers et al., 2000; MacDonald and Grieve, 1988). However, these characteristics are detrimental to well completion and workover operations because they lead to difficult filter-cake cleanup, poor cementing, and the retention of oil on cuttings (Davison et al., 2000; Hemphill and Larsen, 1996; Malachosky et al., 1993; Oakley et al., 1991; Saasen et al., 2001; Yan, 2013). Fluids that are highly oil-wetting also tend to alter the wettability of the drilled formation, resulting in formation damage (Ballard and Dawe, 1998; Chen et al., 2006; Cuiec, 1989; Fjelde, 2009; Gant and Anderson, 1988; McDonald and Buller, 1992; Skalli et al., 2006; Yan et al., 1993; Yan and Sharma, 1989). For these reasons, the ability to reversibly control the emulsion and/or

wetting characteristics is beneficial to the design of drilling and completion fluids.

Reversible invert emulsion mud (RIEM) is a newly developed technology that uses a class of ethoxylated alkylamine amphiphiles as emulsifiers (Patel, 1999). These molecules are composed of a C8 to C22 hydrocarbon chain for the lipophilic portion and an ethoxylated amine for the hydrophilic portion. These molecules are reversible; that is, they are strong invert emulsifiers in the presence of a base but become regular emulsifiers in the presence of an acid (Fig. 1) (Patel and Ali, 2003). It has been reported that this reversibility allows the drilling fluid to change from an invert emulsion, i.e., water-in-oil, to a regular emulsion, i.e., oil-in-water, at different stages of the drilling/completion operation. During drilling, the drilling fluid can be used as an invert emulsion with all the performance benefits associated with oil-based muds (OBMs). During and after the completion stage, the emulsion can be reversed by adding a water-soluble acid, thus providing excellent filter-cake cleanup, better cementing, improved production in well completion, efficient cutting cleanup, and waste minimization (Ali et al., 2004, 2006; Green et al., 2001; Patel, 1999; Patel and Growcock, 1999; Patel and Ali, 2003).

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**Fig. 1.** Chemical structure and protonation formula of ethoxylated alkylamine surfactants (R is a mixture of C14–C18 aliphatic hydrocarbons, C18=67%, C16=30%, C14=3%;  $m=n=1$ ).

Because the unique attribute of RIEM in the completion of a well is supported by the pH-responsiveness of ethoxylated alkylamine emulsifiers, it is important to explore how pH levels influence the interfacial gathering behaviors of the emulsifiers and thus the completion performance of RIEM. A limited number of publications on this topic can be found in the literature. Several authors (Ali et al., 2004, 2006; Green et al., 2001; Patel, 1999; Patel and Growcock, 1999; Patel and Ali, 2003) reported that low pH promotes the transformation of RIEMs from a water-in-oil type to an oil-in-water type, inducing the water wetting condition of the surfaces of the pipes and the drilled formation. Bryant et al. (2006) has demonstrated that the adsorption of ethoxylated alkylamines affects the wettability of mica surfaces. In particular, he showed that low pH levels promote the adsorption of ethoxylated alkylamines, resulting in a stronger oil-wetting condition of the mica surface. Above pH 8 or 9, no ethoxylated alkylamines remained adsorbed, and the mica surface was restored to water-wetting conditions. At present, there is no consistent understanding of the pH-responsiveness of the wetting behavior of ethoxylated alkylamines. Moreover, the effects of the pH of the cleaning fluid on the cleanup of RIEMs and the mechanisms involved have not yet been studied.

In the present work, four cleaning fluids with various pH levels are evaluated using siliceous samples contaminated with RIEM to gauge how pH affects the cleanup of RIEMs. Next, the potentials for formation damage are evaluated. The goal is to identify the cleanup characteristics of RIEMs and the completion performance of wells drilled with RIEMs. The pH-responsive behaviors and chemical states of emulsifiers at both the water-oil and liquid-solid interfaces are also investigated to determine their fundamental mechanisms. Based on the available data, an improved cleaning method is proposed for RIEMs.

## 2. Experimental section

### 2.1. Materials

**Solid samples:** The sandstone core plugs used in the RIEM formation damage test were 25 mm in diameter and 60 mm in length with 850 md permeability and 24.5% porosity. The sandstone disks and cuttings used in the RIEM-cleanup test were produced by slicing and smashing sandstone core plugs, respectively. The quartz crystals used to measure the contact angle is composed of 99.99% silica, and has a melting point of 1750 °C, a mohs hardness of 7 and a density of 2.2 kg/m<sup>3</sup>.

**Liquid samples:** The RIEM was prepared with the formation listed in Table 1. The reversible emulsifier used in RIEM is an ethoxylated tallow amine, with a purity of >97%. Its chemical structure is shown in Fig. 1. Four buffered brines were used as cleanup fluids: pH 4, pH 6, pH 8 and pH 10. NaCl was added as needed to maintain a constant ionic concentration of 0.1 M. The compositions of the four cleaning fluids are listed in Table 2.

### 2.2. RIEM cleanup test

We first mimicked the way that RIEM touched the siliceous rock in the wellbore, and then used cleaning fluids with various

**Table 1**  
Formation for RIEM (10.0 lb/gal, 50:50 O/W ratio).

Composition	Weight (g)
5# White oil	174
Reversible emulsifier	14.5
25% CaCl <sub>2</sub> brine	246
Lime	2
Organoclay	4
CaCO <sub>3</sub>	158

**Table 2**  
Compositions of cleaning fluids.

Composition	pH 4, 0.1 M	pH 6, 0.1 M	pH 8, 0.1 M	pH 10, 0.1 M
NaCl (g/L)	3.7402			
Na Acetate (g/L)	2.9531			
Glacial HAc (mL/L)	3.7			
Na <sub>2</sub> HPO <sub>4</sub> (g/L)		0.932	6.2108	
NaH <sub>2</sub> PO <sub>4</sub>		6.45	0.3179	
NaHCO <sub>3</sub> (g/L)				2.1003
NaOH (g/L)				0.4280

pH levels to remove RIEM in order to gauge how pH affects the cleanup of RIEM. (1) The RIEM filter-cake was built statically on a sandstone disk using high-temperature/high-pressure equipment at 80 °C and 500 psi and then soaked in the cleaning fluids. Following soaking, the efficiency of filter-cake removal was recorded. (2) Sandstone cuttings were dried at 105 °C for 3 h and then hot-rolled in RIEM at 80 °C for 2 h. Next, the cuttings were separated on a screen and soaked in the cleaning fluids. Following soaking, the mud-removal efficiency was recorded. (3) Six quartz plates were cleaned with ethyl alcohol and then simultaneously soaked in brine (0.1 M NaCl) for 16 h at room temperature. One of these pretreated plates was used to test the initial conditions. The remaining plates were soaked in solids-free RIEM for 4 h and then washed several times with cleaning fluids. Finally, the RIEM-removal efficiency was observed and recorded. The surface conditions of the quartz plates were investigated using contact angle and Fourier transform infrared spectroscopy (FTIR) measurements. The microstructures of the solids-free RIEMs treated with various cleaning fluids were investigated with microscopy.

### 2.3. RIEM formation damage test

A high temperature-high pressure core flooding apparatus was utilized for return permeability experiments. (1) The core plug was mounted in the core holder after saturation with synthetic brine overnight. Kerosene was injected in the production direction at a flow rate of 1 mL/min through the saturated core sample for 24 h to achieve irreducible water saturation. The base permeability of the core sample was measured by injecting kerosene in the production direction at a constant flow rate of 1 mL/min. (2) Seven pore volumes of the RIEM were then injected into the core sample to simulate RIEM formation damage. The flow direction of the RIEM was opposite that of the base permeability. Finally, the RIEM soaked for 4 h at a temperature of 80 °C, and the return permeability was measured using the same method used to measure the base permeability. (3) To simulate the effect of the pH buffer on formation damage, seven pore volumes of the pH buffer were injected to soak the core sample damaged by RIEM. The conditions for the injection and soaking were the same as those for the RIEM formation damage test. The return permeability was then measured and compared with the base permeability.

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