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# Low- Viscosity, Direct- Emulsion Drilling Fluid Addresses Conventional Emulsion System Limitations

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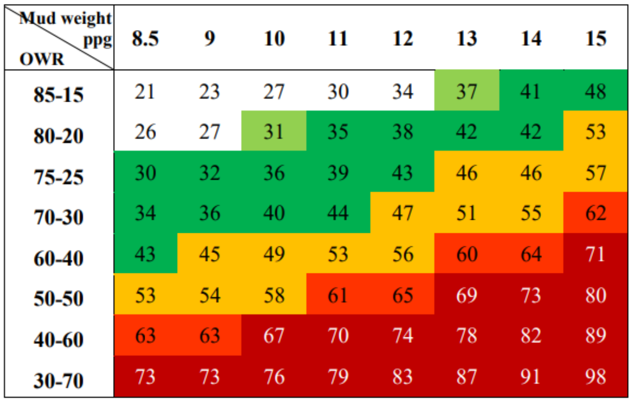
## Abstract

Brine-based direct emulsion drilling fluids are used to drill formations with a high potential of water or brine invasion from salt formations. Forming a direct emulsion in saturated brine that also contains divalent ions is extremely challenging. The oil and gas industry relies on excessive viscosity to stabilize direct emulsions which causes entrapped air in the fluid, foaming, and excessive corrosion. This paper presents the development of a direct emulsion drilling fluid that does not rely on viscosity to maintain emulsion stability and is designed to address the shortcomings of more conventional direct emulsion systems. Structure-activity analysis of emulsifiers was performed in a diesel-brine emulsion. Foaming, corrosion protection, and the ability to recycle oil was correlated with surfactant structures. Fluid system stability was checked by thermal aging of formed emulsions. A design of experiments method was used to optimize surfactant and co-surfactant package and treatment quantity to achieve a cost-effective solution. The ability to separate and recycle emulsion phases was evaluated based on analysis of surfactant physiochemical properties. Separation of the emulsion was verified and partitioning of emulsifier between layers was confirmed by reforming a new emulsion. The preceding direct emulsion system was reformulated to create a new drilling fluid system fully surfactant dependent, with an innovative low-foaming surfactant, that stabilizes oil-in-water emulsions and eliminates the dependency on a polymeric viscosifier. The new drilling fluid system lessens the potential risk of fluid aeration, therefore diminishing corrosion potential and resolving any field problems related to aeration during drilling. Additional development studies were conducted by using corrosion control tests, foaming tests, and large-scale mixes. Furthermore, lubricity of the new system is improved versus designs that rely on viscosity to stabilize the emulsion. Environmental evaluation was conducted, and as expected, the highly efficient emulsifier reduces mobility of oils in water streams which may well increase toxicity of the system in the case of a spill. The latest version of direct emulsion drilling fluid system addresses issues versus conventional highly viscous direct emulsion systems. This paper presents the approaches, used by authors, and based on sound structure-activity analysis is proved successful and are a preferred way for the industry to develop new products. Furthermore, this approach reduces the number of components required to form a system and builds in the potential for recycling the oil.

## Introduction

Minimizing the interaction of fluid with a salt formation is possible in two ways, either with oil-based mud (OBM) or saturated brine fluid. The challenge with using an OBM is that an invert emulsion has only moderate ability to accept additional internal phase before viscosity becomes too high (Figure 1). Due to specific salt formations being drilled, influx of formation fluid is expected; therefore, maintaining an invert emulsion mud at acceptable viscosity with increasing internal phase fraction will be challenging.



| Mud weight ppg / OWR | 8.5 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|
| 85-15 | 21 | 23 | 27 | 30 | 34 | 37 | 41 | 48 |
| 80-20 | 26 | 27 | 31 | 35 | 38 | 42 | 42 | 53 |
| 75-25 | 30 | 32 | 36 | 39 | 43 | 46 | 46 | 57 |
| 70-30 | 34 | 36 | 40 | 44 | 47 | 51 | 55 | 62 |
| 60-40 | 43 | 45 | 49 | 53 | 56 | 60 | 64 | 71 |
| 50-50 | 53 | 54 | 58 | 61 | 65 | 69 | 73 | 80 |
| 40-60 | 63 | 63 | 67 | 70 | 74 | 78 | 82 | 89 |
| 30-70 | 73 | 73 | 76 | 79 | 83 | 87 | 91 | 98 |

Figure 1. Calculation of OBM density vs. internal phase volume fraction showing under which conditions particle movement becomes hindered and viscosity increases substantially.

Alternatively, aqueous fluids can be utilized which can tolerate influx of formation fluid better than OBM; however, due to drilling through salt zones, aqueous fluid must be formulated with saturated brine to avoid wellbore washout. The issue when drilling with saturated brine is the density. Due to low formation fracture gradient, density of the fluid needs to be less than 10 lbm/gal (saturated NaCl). This is clear brine fluid without consideration of low-gravity solids (LGS), which will further increase fluid density. Reduction of density is possible by incorporating various low-density additives – such as glass beads, ground rubber, or lower density fluid. Adding diesel is the most economically viable method of addressing excessive density when using saturated NaCl brine. Diesel density is 6.5 lbm/gal vs. 10 lbm/gal for saturated NaCl brine; therefore, only moderate amounts of diesel are required to reduce the drilling fluid density.

## Problem Statement

Preparing a stable direct emulsion fluid in saturated NaCl brine is a challenge. The reason for this challenge is there exists an exceptionally large density difference between the brine phase and diesel phase (10.0 lbm/gal vs. 6.5 lbm/gal), which makes it extremely difficult to keep the phases from separating. High concentration of electrolytes also decreases the performance of many common emulsifiers normally available to form a direct emulsion. Furthermore, presence of contaminants such as calcium or iron further increases the challenge of creating a stable and cost-effective solution. One common method in preparing a direct emulsion fluid was to consider is a viscosity-stabilized emulsion where the brine phase is viscosified with xanthan to prevent diesel particles from separating. However, a xanthan stabilized system proved to be difficult to deal with in the field due to calcium contamination and entrained air. Furthermore, excessive fluid viscosity increased corrosion rates. Several direct emulsifiers from suppliers have been evaluated. None of these emulsifiers formed a direct emulsion of sufficient stability using conventional emulsification methods i.e. form an emulsion without excessive shear. Furthermore, in several instances, vendor-proposed solutions using sulphonated asphalt simply darkened the mixture to the point where it became difficult to determine if the emulsion formed; however, upon closer inspection, it was determined that a direct emulsion did not form.

## Discussion and Results

The search for surfactants resulted in a chemistry that can stabilize direct emulsions with low density oil in saturated brine with minimal shear and provide a cost effective solution to meet the challenge. Figure 2 shows a comparison of new low-viscosity direct emulsion system and old xanthan-based direct emulsion system. Lighter pink color (due to red diesel) indicates smaller internal phase droplets for the new system. Also, while the new low-viscosity system has a small number of surface bubbles, they dissipate quickly. When density is measured without a pressurized balance the result is 9.0 lbm/gal, which is on target. The high viscosity required to mechanically stabilize diesel droplet dispersion in the old xanthan-based system tends to entrap air, and the fluid density is 8.43 lbm/gal, which is 0.57 lbm/fal below target. The choice of chemistry was driven by high stability in contaminated fluids and low foaming. While a similar class of surfactants are also reasonably effective, their tendency to foam causes similar issues that were identified in previous field trials and are goals aimed at being addressed with the new system.

Figure 2. (left) New low-viscosity direct emulsion and (right) old xanthan-based solution.

To further demonstrate the new system's stability, the fluids were hot rolled at 150°F x 16hrs and, additionally, static aged at 150°F x 3 days. The new system proved successful in ongoing performance testing, solids contamination, proving to have a strong emulsion stability.

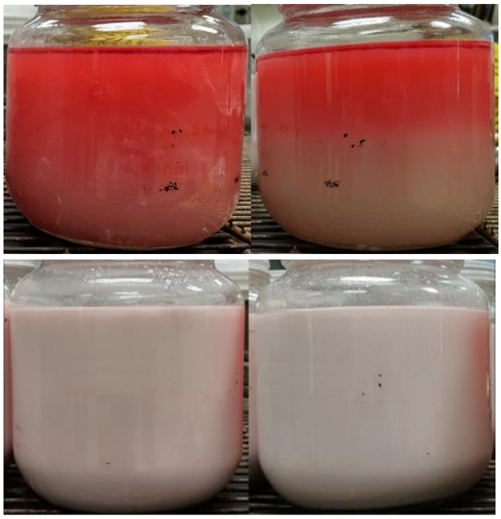
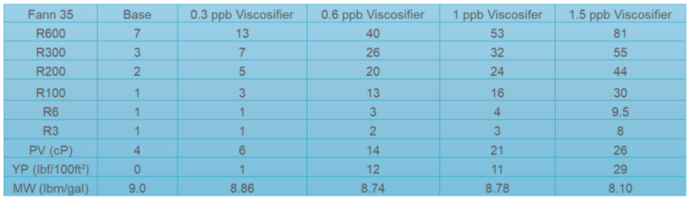


Figure 3. Large-scale Mix: Xanthan-stabilized direct emulsion (top left – AHR, top right – ASA) and surfactant-stabilized direct emulsion (bottom left – AHR, bottom right – ASA).

The new system clearly shows superior stability even without viscosity due to the carefully tuned surfactant system. In Figure 3, large-scale one barrel mixes were performed and collected into glass jars showing emulsion stability BHR and AHR at 150°F x 16 hours. Then the samples were tested for foaming and system aeration. Surface foam testing was recorded after mixing for both samples. The conventional high-viscosity direct emulsion resulted in having 1.5x more foam than the new low-viscosity surfactant stable direct emulsion. As for determining system aeration, the new low-viscosity system's density was precise while the conventional high-viscosity system's density was 0.5 lbm/gal below target. Testing for lime tolerance has demonstrated that our surfactant is resistant to lime. In fact, for health, safety, and environmental (HSE) reasons, the decision was made to adjust pH of the mud with lime to avoid handling caustic. The system showed superior stability up to 6 lbm/bbl lime and possibly more. Lime does not increase viscosity of the system because the surfactant effectively disperses lime soaps. The system can also be effectively formulated over a wide range of brine-diesel ratios to control viscosity and density of the system (see Figure 4). In addition, the new low-viscosity system being emulsion stable at wide range of brine-oil ratios (BOR) shows the new system can handle various amounts of water influx.

Figure 4. Surfactant-stabilized direct emulsion at various brine-diesel-ratios showing good initial, AHR, and ASA stability

The new system's dependency on only using a surfactant for emulsion stability promotes a low rheological profile. However, if viscosity is necessary for cuttings transport or anti-settling properties, the system can be viscosified in a similar manner to previous xanthan-stabilized fluid. Because xanthan is longer relied upon to stabilize the emulsion, the operator has more choice in tuning the viscosity – as shown in Table 1. As seen below, the baseline viscosity is low. As expected, increasing viscosity also increases fluid aeration tendency which is observed by decrease in mud weight when measured without pressurized balance.



| Fann 35 | Base | 0.3 ppb Viscosifier | 0.6 ppb Viscosifier | 1 ppb Viscosifer | 1.5 ppb Viscosifier |
|---|---|---|---|---|---|
| R600 | 7 | 13 | 40 | 53 | 81 |
| R300 | 3 | 7 | 26 | 32 | 55 |
| R200 | 2 | 5 | 20 | 24 | 44 |
| R100 | 1 | 3 | 13 | 16 | 30 |
| R6 | 1 | 1 | 3 | 4 | 9.5 |
| R3 | 1 | 1 | 2 | 3 | 8 |
| PV (cP) | 4 | 6 | 14 | 21 | 26 |
| YP (lbf/100ft$^2$) | 0 | 1 | 12 | 11 | 29 |
| MW (lbm/gal) | 9.0 | 8.86 | 8.74 | 8.78 | 8.10 |

Table 1. New direct emulsion with viscosifier summary.

In the event of fluid aeration, using a pressurized balance would provide accurate mud density readings by eliminating air entrapment within the mud balance. In conventional direct emulsion systems, the issue of aeration plays an increased role in corrosion. Direct emulsion fluids have high electrolyte concentrations when in contact with drilling equipment. Coupled with increased oxygen concentration due to aeration leads to corrosion rates that can increase unless paired with aggressive treatment to prevent corrosion. The new surfactant used provides anticorrosion protection on metal surfaces. Combined with decreased aeration tendency, the new system surpasses the conventional xanthan-stabilized direct emulsion in laboratory corrosion tests (Table 2).

Another added benefit to the low-viscosity direct emulsion fluid was improved lubricity due to the nature of the surfactant. The new low-viscosity system showed a lower coefficient of friction (CoF) to diesel (see Table 3). Solids were added to the low viscosity system and results were similar to diesel. Further lubricity studies were used with the Falex Pin & Vee Block tester with the new low-viscosity have consistently low results (see Table 4).

| Fluid | Corrosion Rate (mpy) |
|---|---|
| Field brine | 2.91 |
| Field brine pH=10 | 1.65 |
| Viscosified Direct Emulsion Fluid | 2.16 |
| Low-Viscosity Direct Emulsion Fluid | 0.05 |

Table 2, Corrosion protection testing results.

| Fluid | OFI Lubricity (CoF) |
|---|---|
| Field brine | 0.25 |
| Diesel | 0.05 |
| Viscosified Direct Emulsion Fluid | 0.08 |
| Low-Viscosity Direct Emulsion Fluid | 0.03 |
| Low-Viscosity Fluid + Solids | 0.05 |

Table 3, OFI Lubricity Testing

| Falex Pin & Vee Block Tester | Field brine | Viscosified Fluid | Low-Viscosity Fluid |
|---|---|---|---|
| Lubricity, CoF, 300 psi | 0.32 | 0.11 | 0.08 |
| Lubricity, CoF, 500 psi | 0.33 | 0.09 | 0.08 |
| Lubricity, CoF, 750 psi | 0.29 | 0.1 | 0.08 |
| Lubricity, CoF, 1000 psi | 0.24 | 0.14 | 0.06 |

Table 4, Falex Pin & Vee Block Tester

Initially formulated with diesel as the internal phase due to economic considerations for locations where direct emulsion can be used, the decision was made to evaluate the ability of the new system to form direct emulsions with alternative oils. Similar surfactant loadings to diesel-based direct emulsions were used with results shown in Figure 5.

Figure 5. Direct emulsion in saturated NaCl brine for alternative base oils (paraffin and mineral oil).

Finally, as part of the sustainability efforts, the ability to reclaim diesel from the phase separated emulsion was examined. Normally this process is performed by introducing demulsifies into the system. Challenges with demulsification occur when the demulsifying chemicals are more soluble in diesel than in the aqueous phase, thus, the result is a diesel phase containing the demulsifier. Diesel containing demulsifying chemistry is very difficult to emulsify even with significant addition of surfactants and shear, thus, making the reclaimed diesel difficult to re-use. Taking advantage of the unique physiochemical properties of the new emulsifier, it was determined to simply separate the phases by pH adjustment. The emulsifier is anionic and when protonated with acid, becomes a less efficient emulsifier leading to phase separation. Figure 6 shows a calculated species distribution under which the emulsifier conditions remain anionic. As shown in Figure 6, at pH of 3 to 4, the majority of the emulsifier converts to neutral inactive species. pH adjustment reduces the content of active anionic emulsifier in the system and the emulsion separates. With increasing pH, the surfactant ionizes quickly and a direct emulsion can reform. Further, note that the salts formed from the up and down pH adjustment, do not affect the stability of the emulsion because the brine contains a high concentration of salts.

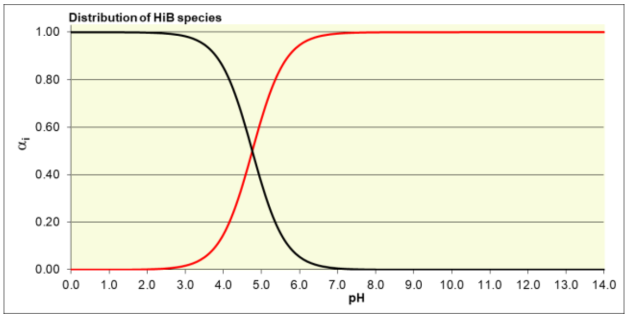


Figure 6. Calculated species distribution of the emulsifier. Black – neutral, red – anionic.

Figure 7 shows that acidification results in total phase separation occurs in minutes. The right pair of images show that the surfactant remains wholly in the diesel phase. Re-using the brine phase does not reform a direct emulsion after pH increase while the diesel phase can be re-used easily because it still contains the surfactant.

Alternatively, typical water treatment chemicals can be applied to flocculate and remove solids without affecting the emulsion quality – as shown in Figure 8

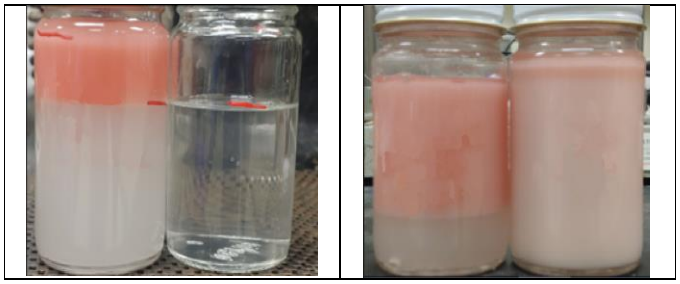


Figure 7. (Left) Separated direct emulsion with a reference container showing that ~100% phase separation. (Right) Reusing the brine phase after separation does not form a stable emulsion while reusing the diesel phase makes new direct emulsion.

Figure 8. Solids-laden direct emulsion(left) and flocculated solids(right) with emulsion still intact.

## Conclusion

A surfactant stable direct emulsion system of diesel in saturated NaCl brine that is also tolerant to high calcium contamination can be formed with proper selection of surfactants. The surfactant stable low-viscosity direct emulsion handles solids contamination and a wide range of BOR making water influx irrelevant. The low viscosity feature allows the new system to achieve decreased surface foam and no system aeration, therefore, resulting in minimal corrosion. Taking advantage of the surfactant's chemistry and utilizing its pH-response feature, it demonstrated that the emulsion can easily be destabilized, and the oil phase can be separated. Additionally, the surfactant remains in the oil phase, increasing the potential for reusing the system, thus, increasing sustainability over high-viscosity xanthan-stabilized direct emulsion systems. Moderate viscosity of the system, coupled with high stability, allows the use of common water treatment additives to remove solids without destabilizing the direct emulsion. Structure-activity optimization of the surfactant allows for a system that is functional, reusable, and prevents issues in the field from corrosion, entrapped air, or foaming.

## Definitions

NaCl = Sodium Chloride
°F = Degrees Fahrenheit
BHR = Before Hot Roll
AHR = After Hot Roll
ASA = After Static Aging
h = hours
mpy = Milligrams per year
OBM = Oil-based Mud
BOR = Brine-oil ratio
lbm/gal = pounds per gallon
lbm/bbl = pounds per barrel
LGS = Low-gravity solids
HSE = Health, Safety, and Environmental
CoF = Coefficient of Friction
PV = Plastic viscosity
YP = Yield point
MW = Mud weight

## References

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