AADE-18-FTCE-077

# Magnetorheological Drilling Fluids: Modification of Viscosity Downhole

Garrett Nielsen, Babak Akbari, and John E. Estrada-Giraldo, Louisiana State University



## Abstract

A magnetorheological drilling fluid prototype has been created that allows for the yield stress of the fluid to be varied downhole, through application of a magnetic tool. These downhole yield stress variations, which can be up to several orders of magnitude, allow for the creation of pressure drops within the annulus that act like "pseudo downhole chokes". These increases in yield stress will only occur over the desired interval, set by the tool length. The magnetorheological drilling fluid is created through the replacement of traditional weighting materials with ferromagnetic weighting materials. Using the aforementioned pseudo downhole chokes, the operator could control the influx from a shallow gas well without exceeding downhole pressure limits, at multiple points, predetermined by shallower formation integrity.

This technology could potentially enable us to safely drill these formations when standard influx and pressure control methods such as closing a BOP would be unfeasible due to the characteristics of the weaker formations in the open hole which could result in underground blowouts or loss of hole. Another proposed use for this technology would be to better navigate tighter mud weight windows typically seen at greater depths in ways that cannot be accomplished with current managed pressure drilling technology in order to extend casing setting points. This could allow for the drilling to hydrocarbon bearing formations that were previously unobtainable due to the complicated mud windows involved.

## Introduction

The problem of uncontrolled shallow gas influx is nothing new, and neither are the industry's attempts to control them. There are many problems that prevent, or hinder typical well control methods. There have also been many suggestions of how to properly handle these inflows. These include, but are not limited to, dynamic kill, pumping heavy slugs, and pilot holes. [1]

We believe that magnetorheological fluids can be applied in drilling systems for better annular pressure control in challenging situations. A magnetorheological fluid is a fluid whose rheological properties, specifically its yield stress, are altered when under the influence of a magnetic field. By changing all, or just a portion, of the weighting material from barite to iron particles it is possible to turn current drilling fluids into magnetorheological drilling fluids. It can then be combined with a downhole tool that contains either permanent magnets, or an electromagnet. This could result in pressure drops of the operator's determined length and magnitude.

Bench top experiments, as well as flow-loop lab experiments were carried out in order to investigate the feasibility of this new technology.

## Magnetorheological fluid

The magnetorheological fluid was created through the replacement of API barite with iron microspheres. Aside from the composition difference between the weighting materials, the iron microspheres were rounder and smoother. See figures 1 and 2 for comparison.

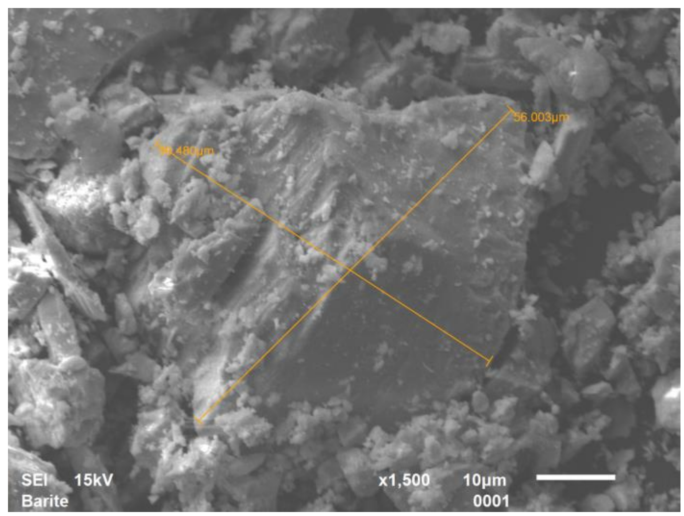


Figure 1: SEM image of barite

### *Particles*

The iron particles were synthetically created iron microspheres. The diameters of these particles ranged from 1 to 10 micrometers. The particles were uncoated, and almost entirely pure iron.

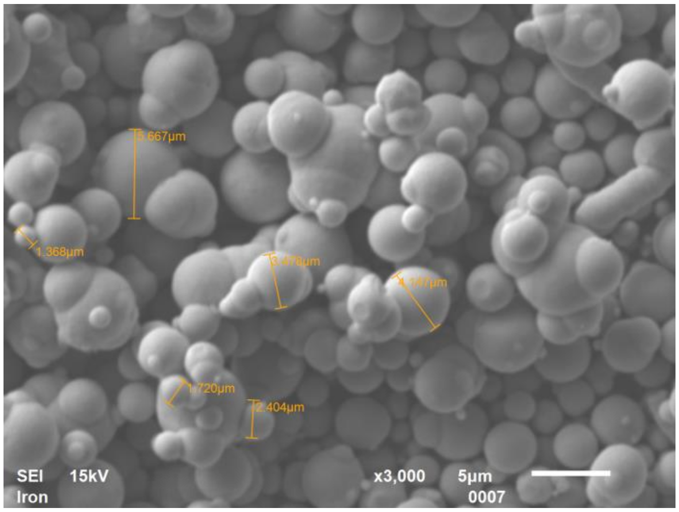

Figure 2: SEM image of iron microspheres

### *Magnetorheological effect*

When a magnetic field is applied, the iron particles align themselves with the magnetic field and create a barrier to flow. The particles are attracted to each other due to the magnetic dipoles they obtain while under the influence of the magnetic field, resembling a chain of particles [2][3][4]. The strength of this effect is dependent on the strength of the magnetic field, as well as the volume percent of ferromagnetic materials [3].

### *Potential Corrosion and Erosion*

Most of the industry would turn their back the second they heard someone say metal particles, with it bringing up bad memories of hematite and ilmenite use in the past, but studies have shown that particle size [5] and shape [6] are more important than the particles hardness. Some studies have even shown that these harder materials, at the right size, are less abrasive than API barite [1].

Another potential problem is the corrosion that would be associated with pure iron particles being placed in a fluid inside of carbon steel pipes. It is possible to greatly reduce the amount of corrosion by coating these particles with minimal effect on the magnetorheological response of the fluid [7] [8] [9] [10] [11] [12].

## Fluid Rheology Test

Prior to tests in a low loop, potential mud samples were mixed at lab scales (350mL samples) in order to determine reasonable amounts of viscosifying agents and weighting materials to be added for larger experiments. This was done through the creation and testing of water based version of both more traditional bentonite/barite muds as well as the magnetorheological bentonite/iron muds. Samples were created using and tested using API 13B-1 standards with a Fann 35 A rotating bob viscometer.

### *Sample Creation*

First 350mL of soft water was mixed with different amounts of bentonite for 10 minutes. These mixtures were then allowed to sit and hydrate for 24 hours before being mixed with their respective weighting materials. Weighting materials of either barite, or iron microspheres were then added to the hydrated bentonite samples and allowed to mix for an additional 10 minutes. All mixing took place in a drink mixer at the mixer's 17,000rpm setting.

Table 1: Sample Information

| Name | Bentonite | Barite | Iron |
|---|---|---|---|
| Sample 0.2 | 30g | 48g | 0 |
| Sample 1 | 30g | 0 | 41.53g |
| Sample 2 | 25g | 0 | 41.6g |
| Sample 3 | 20g | 0 | 41.51g |
| Sample 4 | 20g | 0 | 82.16g |
| Sample 6 | 23g | 0 | 41.08g |
| Sample 7 | 23g | 0 | 41.03g |
| Sample 8 | 23g | 0 | 41.14g |
| Sample 9 | 23g | 0 | 41g |
| Sample 10 | 23g | 0 | 41g |
| Flow Loop | 23lbs./bbl. | 0 | 41lbs./bbl. |

### *Barite Samples*

Sample 0.2 was designed to have a base reading to compare the magnetorheological fluid against.

A larger 55 gallon sample was mixed for use in the flow loop using 23 lbs. / bbl. bentonite and 48 lbs. / bbl. barite. The reason for using a different amount of bentonite for the flow loop sample was so that the amount of bentonite would be the same in both the "normal" and the magnetorheological fluids in order to simulate replacing the barite with iron.

### *Iron Microsphere Samples*

Multiple samples of iron microspheres and bentonite were created using 23 grams of bentonite and 41 grams of iron particles per sample.

EDS, which quantitatively examines the elements present, was used to confirm that the iron particles were indeed embedded in the bentonite, and did not show significant chemical changes otherwise.

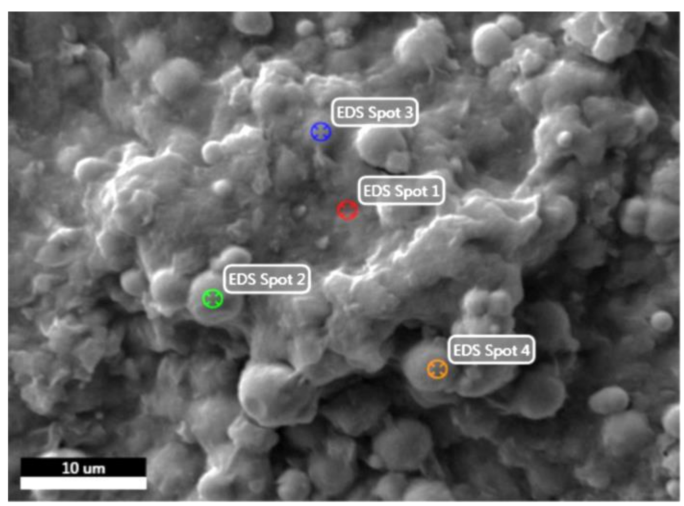

Figure 3: SEM image with EDS locations for sample 10

Table 2: Data for EDS Spot 3:

| Element | Weight % | Atomic % | Error % |
|---|---|---|---|
| O K | 26.09 | 49.83 | 6.30 |
| MgK | 1.20 | 1.50 | 9.06 |
| AlK | 5.45 | 6.17 | 6.04 |
| SiK | 13.32 | 14.50 | 4.89 |
| PtM | 3.88 | 0.61 | 5.80 |
| FeK | 50.07 | 27.40 | 2.65 |

## Flow Loop Test

The ultimate objective is to test the magnetorheological fluid in an actual flow loop under the influence of a magnetic field. This is being done through the use of an experimental set-up consisting of an inner pipe with permanent magnets and an outer pipe to create an annulus.

### *Flow Loop Description*

The flow loops consist of an approximately 21 foot long 1 ¼" schedule 40 inner pipe made of 106A carbon steel. This passes through an annular sealing gland into a larger approximately 20 foot long, 4" schedule 40 stainless steel pipe. The end of the outer pipe opposite the annular sealing gland has an end cap on it. This setup simulated standard drilling practices of flowing down an inner drill pipe and circulating up the annulus, with the outlet being close to the sealing gland. Two sets of centralizers were welded to the inner pipe to prevent it from settling on the low side of the 4" outer pipe.

The inner pipe material was chosen as 106A carbon steel in order to create a barrier to prevent the magnets from drastically increasing the yield stress inside the inner pipe and potentially stopping flow. The outer pipe was chosen to be stainless steel. This decision was made so that it would act more like the formations, in the sense that it would have very little effect on the characteristics of the magnetic field compared to the inner pipe.

Figure 4: Magnet rings and centralizer

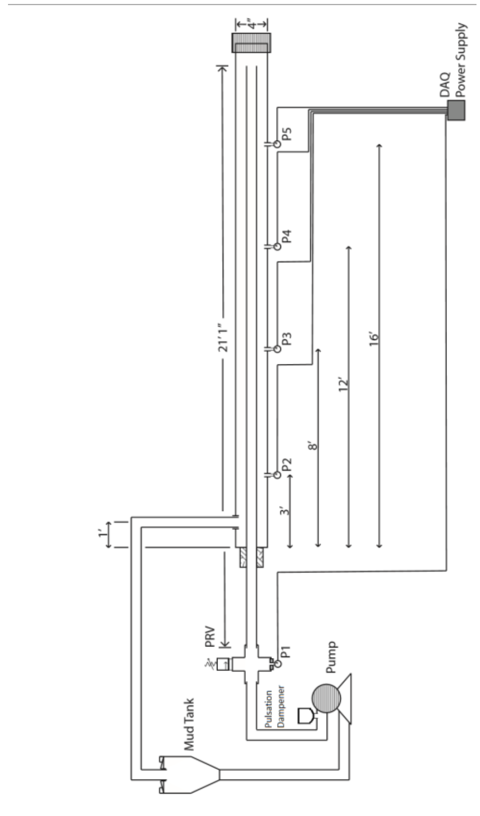


Figure 5: Flow Loop Schematic

The magnetic field for these experiments was generated using permanent magnets, which were attached to the outside of the inner pipe. These magnets were then covered with a thin layer of epoxy to prevent their movement. These magnets were aligned into 2 smaller rings of approximately 0.2 inches axial length each, and 2 larger rings of approximately 0.79 inches axial length. The magnets used were grade N45H neodymium ring segment magnets coated in nickel.

The first (upstream most) magnet ring was composed of small magnets arranged such that their south magnetic dipoles were facing outwards into the annular flow area. The next ring was also composed of small magnets, but arranged such that their north magnetic dipole were pointed into the annular flow area. The next two rings were of the larger magnets and arranged such that the upstream ring had its north magnetic dipole pointed into the annular flow area and the downstream most ring had its south magnetic dipole pointed into the annular flow area. These rings occupied an axial length of only 6 inches in total. Figure 4 shows the magnet rings with epoxy coating.

The magnet ring segments were arranged so that all the magnets on a ring had their dipoles oriented in the same radial direction. The purpose behind this was to prevent the magnetic fields from different dipoles from meeting and canceling out. The same logic was applied for which rings had which dipoles pointed into the annular flow area.

The strength of these magnetic rings ranged from around 3000 Gauss on the outside of the epoxy coating to near 450 Gauss at ½ an inch radially outwards for the larger magnets. The strength near the epoxy was similar for the smaller magnets, but their strength at ½ an inch radially outward was closer to 50-60 Gauss.

Pressure transducers were set up, equidistance, both upstream and downstream of the magnets. The pressure difference between these pressure transducers allowed for a qualitative analysis of the difference between the bentonite/barite and magnetorheological fluid as the fluids weights were increased.

A peristaltic pump, better known throughout the industry as a hose pump, is being used for flow. The peristaltic pump was chosen based on the requirements for a positive displacement pump and our project requirements of having metal parts with very little interaction with the fluid.

Table 3: Fluid Test Results

| | | | | Gel Strength | |
|---|---|---|---|---|---|
| Sample Names | Density | Viscosity | Yield | 10s. | 10 min. |
| Sample 0.2 | 9.35 | 9.5 | 13.5 | 4 | 11 |
| Sample 1 | 9.35 | 14.5 | 33 | 8 | 21 |
| Sample 2 | 9.4 | 13 | 27 | 8 | 19 |
| Sample 3 | | 6 | 9 | 4 | 6 |
| Sample 4 | 10.15 | 9 | 13.5 | 4 | 9 |
| Sample 6 | 9.35 | 9 | 16 | 5 | 9 |
| Sample 2 | | 19 | 28 | 7 | 16 |
| Sample 7 | | 9 | 14 | 4 | 9 |
| Sample 8 | | 9 | 17 | 4 | 9 |
| Sample 9 | | 8 | 16 | 4 | |
| Sample 10 | | 9.5 | 16 | 4.5 | |
| Flow Loop | 9.3 | 13 | 16 | 4 | 9 |

### *Fluid Creation and Testing Procedure*

The mud tank was filled to pre-determined levels and then bentonite was added and allowed to mix for 24 hours. The mixer for the mud tank was turned on to its 1750rpm rating. As previously mentioned the amount of bentonite was approximately the same for each mixture, meaning that the only variable being changed was the type of weighting material being used. The amount of bentonite was approximately 23 lbs. / bbl.

The barite was added in separate batches of 0.575kg per batch, whereas the iron microspheres were added in batches of 0.5kg per batch. These amounts were chosen so that the same number of batches were added in total during the experiments to reach the predetermined amount of weighting material to be added. All batches were pumped through the system at 20 gallons per minute. This gives an average annular velocity of 0.62 ft. /s

### *Flow Loop Results*

The pressure difference between the two middle pressure transducers was plotted against the batch number for both weighting materials. From these results we can see that after enough weighting material has been added (4 batches in our case) a gap develops between the differential pressure seen in the barite experiments and the differential pressure seen in the magnetorheological fluid experiments. Except for an anomaly around 10 batches, this differential pressure gap increased in size up to a maximum near 20 batches.

The drop in pressure seen from 8 to 10 batches for the magnetorheological fluid is likely tied to the fact that those test took place on different days. It is therefore likely that some change in the fluid had occurred. The drop seen from batches 11 to 13 for the barite based fluid occurred across all pressure transducers, and not just across the magnet area. This is also a potential explanation for the magnetorheological pressure change from 8 to 10 batches. It should also be noted that this data is preliminary and only single points for each batch, and the investigation is ongoing.

There is also a noticeable change in the pressure differential starting at 22 batches of iron microspheres. At this point the pressure becomes more dynamic. It is believed that this is the point where a saturation of iron particles has been reached for this particular setup. The results of this saturation would be a bridging of particles and start/stop phenomenon for the flow, where flow stops until a sufficient pressure builds up to break the particles apart and start the process over.

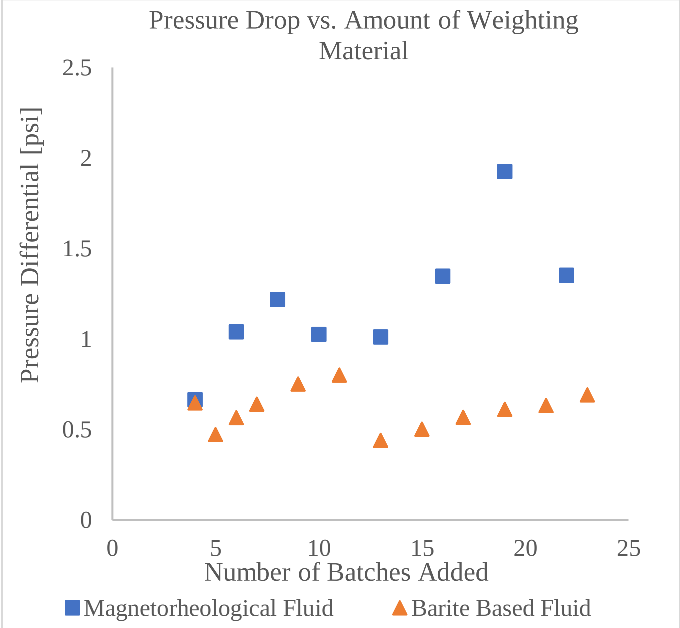


Figure 6: Graph of pressure differential in the annulus across the magnets

### *Benchtop Results of Flow Loop Sample*

The 55 gallon flow loop sample had weighting material added until it reached 23 lbs. / bbl. of bentonite and 41 lbs. / bbl. of iron microspheres. This flow loop sample was created over the course of 6 days. On the 7th day, a small 350mL sample was taken from this to be tested in the lab. All of the rheological and density values were consistent with the previously created lab samples, except for the higher 13cp plastic viscosity.

SEM images and EDS measurements were also taken of these flow loop samples. As seen in figure 8 and table 5, they show similar results to the benchtop samples. It should be noted that the platinum showing up in the EDS measurements is not an error. Platinum is used to coat the samples to prevent them from gaining charge during SEM imaging. Cobalt seen in the EDS image could be attributed to its readings proximity to iron.

### Conclusions

It has been shown that a magnetorheological drilling fluid with stable properties can be created. It has also been shown that standard drill pipe will provide enough magnetic shielding to allow for a magnetic field to be created in the annulus without affecting the fluid inside the drill pipe. The combination of these allows for the creation of pressure drops at locations, and magnitudes, of the operators choosing for whatever purpose the operator envisions.

### Additional Data

Table 3: Data for EDS Spot 1

| Element | Weight % | Atomic % | Error % |
|---|---|---|---|
| O K | 47.30 | 63.44 | 6.75 |
| MgK | 1.30 | 1.15 | 6.07 |
| AlK | 8.53 | 6.79 | 3.95 |
| SiK | 34.94 | 26.69 | 3.40 |
| PtM | 4.09 | 0.45 | 5.46 |
| FeK | 3.84 | 1.48 | 5.50 |

Figure 6: Flow loop

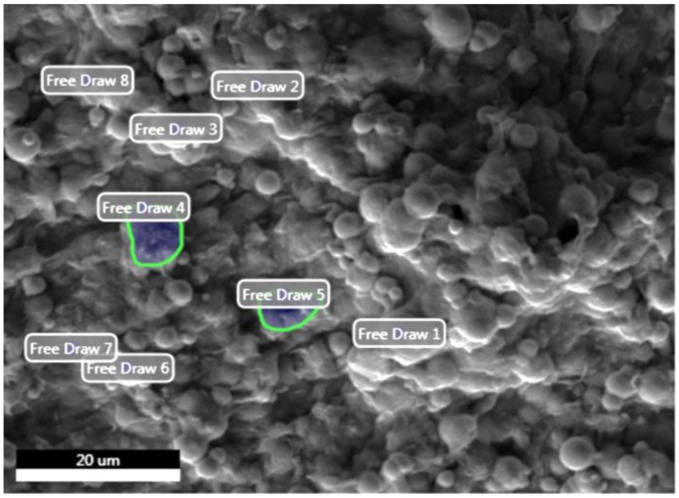


Figure 8: SEM of Flow Loop sample with EDS spots

Table 5: Data for Free Draw 1

| Element | Weight % | Atomic % | Net Int. | Error % |
|---|---|---|---|---|
| O K | 21.80 | 43.61 | 2188.10 | 7.23 |
| NaK | 1.48 | 2.06 | 126.92 | 11.25 |
| AlK | 5.79 | 6.87 | 1043.09 | 6.22 |
| SiK | 19.79 | 22.56 | 3917.40 | 4.77 |
| PtM | 10.64 | 1.75 | 730.60 | 3.27 |
| FeK | 38.60 | 22.12 | 1601.43 | 3.06 |
| CoK | 1.90 | 1.03 | 62.62 | 14.27 |

## Acknowledgments

Thanks to Chevron Innovative Research Support (CIRS) program who provided funding that made the initial set-up preparation possible. We would also like to thank LSU Leveraging Innovation for Technology Transfer (award number LSU-2018-LIFT-008) program for funding the continuation of this project.

Thanks to Douglas Hoy for help with various task throughout the project.

Thanks to AGI Industries for providing an electric motor for the pump.

Thanks to the National Science Foundations I-Corps program for funding travel to discuss this technology with industry.

## Nomenclature

Define symbols used in the text here unless they are explained in the body of the text. Use units where appropriate.

*BHA* = *Bottomhole assembly*
*PPG* = *Pounds per Gallon*
*Cp* = *Centipoise*
*SEM* = *Scanning Electron Microscope*
*Lbs.* = *Pounds*
*Bbl.* = *Barrel*
*EDS* = *Electron Dispersive Spectrometer*
*Ft.* = *Feet*
*S* = *Second*
*DAQ* = *Data Acquisition*

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