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Magnetorheological Fluids for Oil and Gas Well Application

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Magnetorheological Fluids for Oil and Gas Well Application

by

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Report

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Dedication

To my parents, for their support and encouragement

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Abstract

Magnetorheological Fluids for Oil and Gas Well Application

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The University of Texas at Austin, 2015
Supervisors: Eric van Oort, Raissa Douglas Ferron

Cement is used in oil and gas wells to support the casing and prevent fluid migration between formations. Incompetent cementing in a well and the potential subsequent failure of zonal isolation is a significant concern in the oil and gas industry. Insufficient zonal isolation could cause fluid migration resulting in water aquifer contamination and loss of control of well pressure, shortening the life of wells and increasing the risk of well control incidents, which could result in loss of life, economical loss and environmental damage. To achieve good cementation and guarantee zonal isolation during the lifetime of the well, significant technical challenges need to be overcome. Such challenges are associated with guaranteeing proper fluid-cement displacement, preventing gas migration, and maintaining cement integrity during all phases of well life (drilling, completion/stimulation, production, abandonment).

Magnetorheological (MR) fluids (cement-based or non cement-based) can potentially be used to tackle these challenges for applications in oil and gas wells. The rheological properties and flow direction of MR fluids can be controlled by the application of a magnetic field. During the primary cementing process, it is important to displace the drilling fluid and spacer fluid out of the annulus with cement in order to obtain enough strength after cement hydration.

This study shows that by applying a magnetic field, the MR cement-based fluid can be guided to achieve more uniform displacement and to increase the displacement efficiency. The results also show that an MR fluid can be used as a flow prevention seal and has the ability to hold pressure, due to its instantaneous stiffening effect when the magnetic field is applied. This can be applied to avoid or remediate annular fluid flow and gas migration, form temporary top-, bottom- or straddle packers, and combine with BOPs for instantaneous pressure control.

During the production of a well, the cement in the annulus can experience various severe conditions, which can lead to cracking, de-bonding and shear failure of the cement. The magnetic properties of MR cement-based fluid provide a possible way to evaluate the quality of cement, detect cracking in cement and monitor the health of the cement annulus using non-destructive testing with magnetic methods.

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Chapter 1: INTRODUCTION

Competent cementing to achieve lasting zonal isolation is a crucial requirement during well construction. Key to achieving good cementation is proper displacement of drilling fluid out of annular spaces and placement of the cement in them. The viscosity contrast between drilling fluid (Smith and Ravi, 1991), spacers (Maserati et al., 2010) and cement slurries (Li and Novotny, 2006) as well as centralization of the casing in the wellbore (Couturier et al, 1990) are important variables affecting displacement efficiency. For instance, when the casing is not well-centralized in the wellbore, fluids flow more easily and faster through the wider section of the annular gap, while displacement lags behind and may be incomplete in the narrower section of the gap (Couturier et al, 1990, Silva et al., 1996). Such non-uniform displacement and/or incomplete cement placement can lead to unreliable zonal isolation, which in turn may compromise the productive life of the well.

In this graduate report, a new cementing technique is presented wherein the rheological properties and the flow direction of the cement slurry can be controlled in real-time. Such a cementing technique may be useful to achieve more uniform displacements, even when the casing is not optimally centralized. This new technique is based on the principles of magnetorheology, where an external magnetic field is applied to a cement slurry carrying magnetic particles. In the presence of the magnetic field, the viscoelastic properties of such a modified slurry change instantaneously to cause a stiffening behavior characterized by yield point values that are increased by several orders of magnitude (Nair, 2013). By varying the intensity and the direction of the magnetic field as well as the dosage of magnetic particles, the flow properties of the slurry can be altered and the flow can be beneficially directed as desired (Nair and Ferron, 2014).

The magnetorheological (MR) behavior presents other benefits as well. The instantaneous stiffening effect when a magnetic field is switched on may be exploited to generate temporary top-, bottom- or straddle packers for pressure control, and the specific sensitivity of the magnetic slurry to an external field may be exploited for sensing the quality and integrity of cement sheath over the life of the well. Voids, gaps or cracks in the cemented annulus cause disturbances of magnetic field lines that may be picked up by suitable detectors.

Chapter 2 gives brief introductions to well cementing and MR fluids. The possible applications of MR fluids in oil and gas wells are also presented: (1) pressure and flow prevention seals, (2) cement displacement, and (3) cement bond monitoring and voids detection.

Chapter 3 describes the materials used in the study as well as the sample preparation procedures. A Vibrating Sample Magnetometer (VSM) is used to study the magnetic properties of these materials. Finite Element Method Magnetics (FEMM) is used as a tool to conduct simulations for the laboratorial experiment. There is also a detailed explanation of the experimental setups designed to evaluate different applications of MR fluids in oil and gas wells.

Chapter 4 presents the results and discussion for both the FEMM simulations and the laboratorial experiments. The preliminary study on using MR fluids for pressure and flow isolation shows results that are promising, but the ability of our preliminary formulations to hold pressure is still modest. However, further improvement appears to be possible. The cement displacement experiment demonstrates the idea that MR fluids can be tailored and controlled to achieve better displacement efficiency of drilling fluid by MR spacers and cement. The FEMM simulation study on cement bond monitoring and voids detection presents the feasibility of using MR cement as a medium to evaluate the quality of the cement annulus and to conduct health monitoring of it with the non-destructive magnetic measurement.

Chapter 5 summarizes the findings of this study along with a few recommendations for future work.

Chapter 2: BACKGROUND

In this chapter, a brief introduction of well cementing, importance of zonal isolation and the key challenges of cementing are presented. The chapter also includes a section on MR fluids and their potential applications in oil and gas wells.[1]

2.1 INTRODUCTION TO WELL CEMENTING

In oil and gas well applications, cementing (see Figure 2.1) is defined as the process of placing a cement slurry in a well by mixing powdered cement, additives, and water at the surface and then pumping it by hydraulic displacement to the desired locations (Sweatman, 2010). The main purpose of well cementing is to provide zonal isolation for the entire life of the well by restricting fluid movement between formations and providing bonding and support of the casing.

Poor cementation may result in costly remedial work, have a negative influence on hydrocarbon production, may cause water aquifer contamination, and may effectively shorten the productive life of wells. Moreover, poor cementation could also increase the risk of well control incidents (Carter and van Oort, 2014), which could result in economical loss and environmental disasters. One of the most important causes of the Macondo / Deepwater Horizon disaster in 2010 was considered to be the failure of primary foam cementation (Mueller, 2012), which resulted in the loss of lives, the largest offshore oil spill in history, and huge environmental problems in the Gulf of Mexico.

Providing guaranteed zonal isolation is one of the most significant challenges in the oil and gas industries, especially for deep water well cementing, nowadays. Many

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[1] Nair, Sriramya D., Qian Wu, Mike Cowan, and Eric van Oort. 2015. "Cement Displacement and Pressure Control Using Magneto-Rheological Fluids." In proceedings of SPE/IADC Drilling Conference and Exhibition, London, U.K., 2015.

factors of the primary cementing job have an influence on zonal isolation. For example, to provide effective zonal isolation, cement is expected to obtain sufficient compressive strength within a certain amount of time. For deep-water wells, synthetic-based mud (SBM) contamination of the Portland cement slurries can greatly compromise the set slurries' properties such as compressive strength and pump time (Aughenbaugh et al. 2014). Therefore, it is imperative to ensure that the drilling fluid is sufficiently displaced by cement in the annulus to reduce the possibility for contamination-related issues.

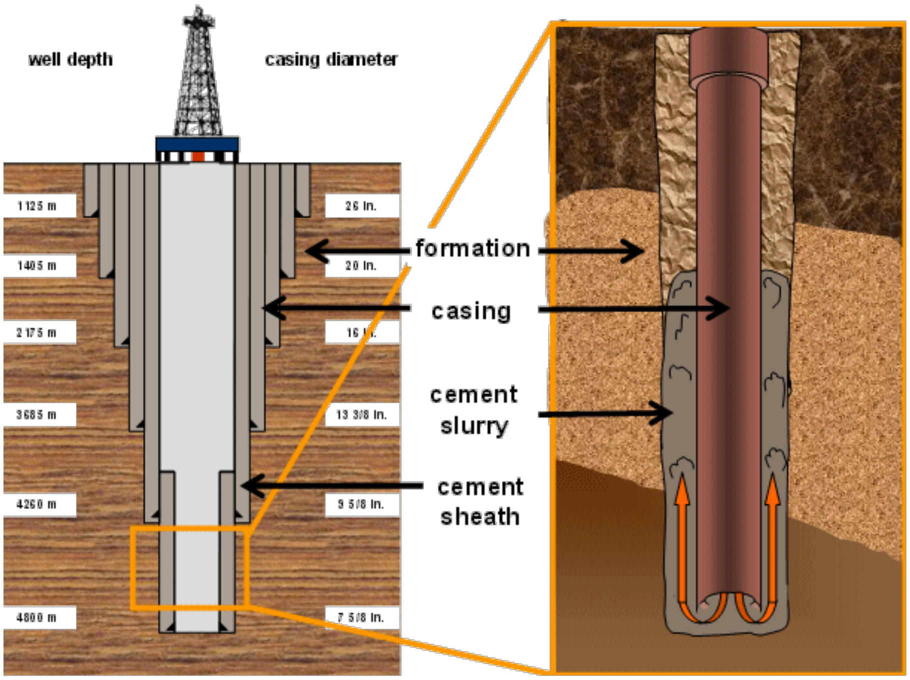

Figure 2.1 Schematic of cased and cemented oil and gas well (left); typical cementing process between formations and casing (Plank, 2015)

2.2 INTRODUCTION TO MAGNETORHEOLOGICAL FLUIDS

Traditional MR fluids consist of magnetic particles that are dispersed in oil or water. Potential benefits are associated with the ability to actively and instantaneously control the viscosity and stiffness of MR fluids as well as the ability to guide such fluids in desired flow directions, all through the manipulation of a magnetic field. The stiffness of an MR fluid can be reversed to its original state when the applied magnetic field is removed, which is one of the important advantages of using MR fluids. A significant number of studies have been conducted to evaluate the changes in rheological properties of MR fluids for several different applications (Klingenberg 2001). It has been shown that by varying the dosage of magnetic particles of a MR fluid and by applying a magnetic field, the yield stress and viscosity of the MR fluid can be increased by orders of magnitude. In related literature, it has also been shown that MR fluids can be prepared by dispersing magnetic particles in a variety of carrier fluids such as mineral oil (Sheng, Flores and Liu 1999; Lim et al. 2004), synthetic oil (Son and Fahrenthold 2012), water (Bica, Vekas, and Rasa 2002), water-based drilling fluid (Lee et al. 2009), and cement paste (Nair and Ferron 2014), etc. This research study is focused on illustrating the use of MR fluids (either drilling fluid-based, spacer-based or cement-based MR fluid) as a way to improve primary well cementation.

MR cement-based fluids (shown in Figure 2.2) are composed of magnetic particles mixed in with the cement, thus making it sensitive to the application of an applied magnetic field. Previous studies on MR cement-based fluids showed that as the magnetic field strength increased from 0 Tesla to 1 Tesla, the yield stresses for all samples increased strongly, which was mainly dependent on the magnetization values of the magnetic particles (Nair, 2013). The yield stress was also dependent on the dosage of the magnetic particles in cement slurry (Nair and Ferron, 2014).

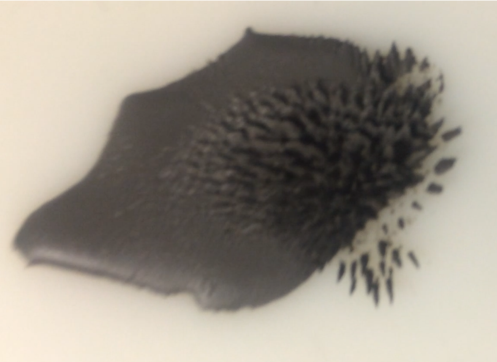

Figure 2.2 Alignment of magnetic particles of a MR cement-based fluid along the direction of applied magnetic field lines

2.3 POTENTIAL ADVANTAGES OF MAGNETORHEOLOGICAL FLUID APPLICATION IN OIL AND GAS WELLS

In this study, we will focus exclusively on the potential merits of MR fluids for pressure and flow prevention, improving cement displacement, and cement annulus monitoring.

As mentioned in the previous section, the active and instantaneous control of the viscosity and stiffness of the MR fluids can be advantageous for withstanding pressure and to prevent flow in the cement annulus. This phenomenon can be applied to several cases for well construction. For example, by using a MR-based drilling fluid or MR-based spacer fluid, any un-cemented channels between the casing and the borehole can be activated with a magnetic field to help form a seal in the annulus, thus providing sufficient zonal isolation. These fluids can also be used to form a pressure and flow-prevention seal in the annulus above the top of cement. This technology can also be used to form a removable or temporary packer[2] for well control, for isolating sections of a wellbore during remedial or recompletion treatments, or during well abandonment. This ability of MR fluid to withstand pressure has been used in several other fields, such as pressure control of high-pressure differential magnetic fluid seals for equipment (Zhou 2003), coaxial twin-shaft magnetic fluid rotary seals (Cong, Dai, and Shi 2009), and actuators (Klingenberg 2001).

In the case of viscosity control, note that cement slurries, spacers and drilling fluids are typically thermally-thinning fluids, in which their respective viscosities decrease with increasing temperature (Nelson and Guillot 2006). For efficient displacement of drilling fluid, cement must maintain an optimum viscosity contrast with respect to the drilling fluid and/or spacer throughout the interval where cement must be placed (Couturler et al. 1990). By controlling the magnitude of the applied magnetic field strength, the rheological properties (e.g. plastic viscosity and yield stress) of the cement-based MR fluid can be controlled in real time, thus increasing the chances of complete displacement.

Active directing of the flow of cement around the casing may help prevent incomplete displacement when the casing inside a well is not sufficiently centralized. This commonly happens in the case of directional / horizontal drilling when casing centralization and the creation of sufficient stand-off are insufficient and/or when the borehole caliper is poor (Nelson and Guillot 2006). In this situation, cement preferably flows through the wider annular gap and drilling fluid is left behind in the narrower gap (Figure 2.3), thus creating a channel for mud flow after cementing. Such non-uniform displacement of drilling fluids and/or incomplete cementation can lead to unreliable zonal

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[2] A packer forms a seal that can be deployed to replace or supplement the cement seal (Board, 2012).

isolation, which may, in turn, compromise the productive life of the well. In this study, we have shown that by using a cement-based MR fluid, and by effectively controlling the magnetic field lines, the cement slurry can be directed into narrower gaps, thus improving the displacement efficiency of drilling fluids.

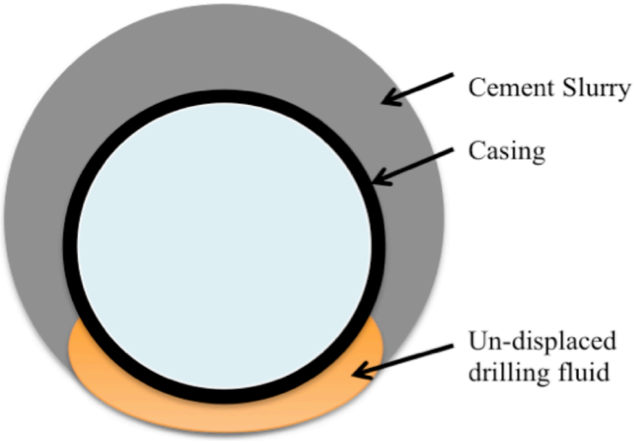

Figure 2.3 Shows the schematic of an eccentric casing in a bore hole. Complete displacement of drilling fluid does not occur in the narrower gap.

The magnetic properties of the MR cement-based fluid provide a potential alternative to existing downhole cement bond logging (CBL) techniques. CBL is evaluation of the presence of cement and its bonding to casing and formation using an acoustic log. Conventional CBL techniques (see Figure 2.4), such as acoustic bond logging, are conducted by running logging tools inside the well (Nelson and Guillot 2006), which involves interruption of production and is a time-consuming operation. Also, the accuracy of the conventional CBL can be affected by various factors, such as the existence of microannulus. Microannulus is a small gap formed due to de-bonding between the cement sheath and the casing or rock formation. Most microannuli are formed due to variations in temperature or pressure during or after the cementing process

(Jutten and Hayman 1993). Temperature cycles cause the relatively stiff cement to swell and contract, inducing tiny cracks (i.e. microannuli). In some cases, the microannulus may not have a significant influence if it's not connected to create a path for any reservoir fluids migrating to the surface. In such cases, remediation might not be required. However, in more severe cases, the microannulus may encircle the entire circumference with long connected channels, which can jeopardize zonal isolation allowing communication of fluids between zones (Shakirah 2008). In conventional CBL, the signal received for the cement sheath with a microannulus (even a non-communicating microannulus) is similar to the signal received when there is only drilling fluid present in the annulus (Jutten and Hayman 1993, van Kuijk et al., 2005). This can cause confusion in interpreting the cement bond logs, leading to costly remedial cementing.

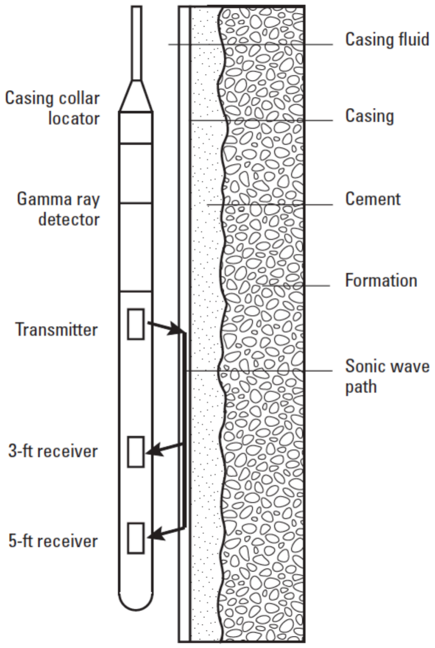

Figure 2.4 Conventional cement bond logging tool configuration, demonstrating that acoustic energy is emitted from the transmitter in all directions and measured by the receivers (Nelson and Guillot 2006)

Magnetic methods have been studied and applied as important non-destructive methods of measurement for a long time. A typical magnetic non-destructive test is the flux leakage detection using magnetic particle inspection, magnetic tape, or sensing coils and probes. In magnetic non-destructive testing, ferromagnetic materials[3] are examined under an external magnetic field. Any resulting changes of magnetic flux in the region of interest are observed and measured (Blitz, 1993). This method is often applied for detecting flaws, measuring dimensional changes, and observing variations in magnetic permeability for ferromagnetic materials. In this study, the possibility of using a MR cement-based fluid as a medium to achieve non-destructive, non-disturbed and long-term health monitoring of the cement annulus will be discussed to evaluate the quality of cement bond as well as to detect the presence of voids and channels.

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[3] Ferromagnetic materials are metallic materials that can be magnetized and strongly attracted to a magnent (Callister and Rethwisch, 2013).

Chapter 3: MATERIALS AND EXPERIMENTAL METHODS

In this chapter, the materials, sample preparation, and experimental setup as well as procedures are discussed. A Vibrating Sample Magnetometer (VSM) is used to study the magnetic properties of materials used in this study. A finite element solver, Finite Element Method Magnetics (FEMM) is presented as a tool to conduct simulations for the laboratorial experiments. The experimental setups to evaluate the applications of MR fluids are also explained in detail.[4]

3.1 MATERIALS AND METHODS

3.1.1 Magnetorheological Fluids

3.1.1.1 Magnetorheological Cement-based Fluid

An American Petroleum Institute (API) class A oil well cement (API-10A 2011) with the specific gravity of 3.14 was used in this study for cement-based MR fluid. Magnetic particles used to prepare MR fluid were iron powders manufactured through thermal decomposition, called carbonyl iron powder (CIP). These particles have a purity of at least 99.5% with the specific gravity of 7.8. All cement slurries were prepared with deionized water. The water-to-cement (w/c) mass ratio was maintained at 0.4 in order to achieve a similar degree of cement hydration. It has been shown in other studies that the addition of iron particles does not affect cement hydration or compressive strength (Nair 2013). The slurries were prepared in a high shear blender (OFITE, Model 20) according

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[4] Nair, Sriramya D., Qian Wu, Mike Cowan, and Eric van Oort. 2015. “Cement Displacement and Pressure Control Using Magneto-Rheological Fluids.” In proceedings of SPE/IADC Drilling Conference and Exhibition, London, U.K., 2015

to the ASTM standard practice for cement slurry (ASTM-C1738 2011).The cement slurry density varied between 16-17 pound per gallon (ppg).

3.1.1.2 Magnetorheological Xanthan Gum Fluid (MR_X)

For the experimental setups I and II, non-cement based MR fluid (denoted as MR_X) was prepared with xanthan gum and magnetic particles (specifically CIP) for ease of clean up and to avoid cement hardening inside the apparatus. Xanthan gum used in this study is a fine white powder with the specific gravity of 1.6 (CP Kelco, KELZAN) The xanthan gum solution is clear without any colors. To prepare MR_X fluid, 2 g of Xanthan gum was dispersed in water per lab barrel (350ml) in a malt cup using a multimixer (Sterling Multi-products, Inc, Model 9B) at 14,000 rpm for 5 minutes The dosage of Xanthan gum was chosen such that the rheological properties were similar to that of a pumpable cement slurry. After preparing the xanthan gum solution, it was allowed to rest for at least 1 hour before mixing 50% CIP particles (by volume) into the fluid using the mud mixer at 14,000 rpm for 30 seconds to obtain MR_X. MR_X fluid presents dark-gray color due to the CIP particles.

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3.1.1.3 Contrast Fluid

For experimental setup II, a clear fluid was prepared to imitate a drilling fluid/spacer fluid. The clear fluid helped with the visualization process to act as a good contrast to the dark colored xanthan gum MR fluid. This clear fluid was also mixed in a mud mixer at 14,000 rpm for 5 minutes by dispersing 1% water-soluble resin (polyethylene oxide with fumed silica by mass, referred to as WSR in water, along with ethanol, per lab barrel of fluid.

3.1.2 Properties of Permanent Magnets

The permanent magnets used in this study were made of Neodymium Iron Boron (NdFeB) rare earth magnetic material with Grade N42. Table 3.1 contains further details about the magnets. The strength of the maximum magnetic field at the surface of the magnets shown in Table 3.1 was measured using a Gaussmeter (AlphaLab, Inc, GM 1-ST). The information regarding the pull force of the magnets was obtained from the manufacturer (K&J Magnetics, Inc). These magnets were magnetized through their thickness. NdFeB magnets are available in ranges from N24 up to N52, where usually a higher grade refers to a stronger magnet (when compared at the same temperature and for the same shape of the magnet). The maximum operating temperature of the N42 magnets shown in Table 3.1 is 176° F (80° C). For high temperature applications, the NdFeB magnets can be used up to an operating temperature of 446° F (230° C) (e-Magnets UK 2014) by altering the composition, geometry and manufacturing conditions. For higher temperature applications, Samarium Cobalt (Sm-Co) rare earth magnets can be used with the maximum operating temperature of 1022° F (550° C) (Electron Energy Corporation 2014).

Table 3.1 Properties of permanent magnets used in this study

Magnet	Type	Dimensions* (in.)	Maximum Surface Field (G)	Pull Force (lb) (Magnet to a Steel Plate)
Type 1	Block	4 × 1 × ½	3400	115
Type 2	Block./Countersunk	2 × 1 × ½	4200	75

*Dimensions are given in the following order: length x width x thickness

3.2 VIBRATING SAMPLE MAGNETOMETER (VSM)

The magnetic properties of samples were obtained using an EV7 vibrating sample magnetometer (VSM, shown in Figure 3.1). A VSM precisely measures the magnetic moment of the sample by vibrating it perpendicularly to a uniform magnetic field in between a few detection coils (Foner 1959). The data obtained from a VSM is useful to plot magnetization curves. The magnetic properties of fresh cement slurries (1 hour after mixing) and 7-day-old hardened cement were measured at 75.2° F (24° C). A 6-mm diameter cup made of ULTEM™ resin with a lid for sealing was used as the sample container. For each sample, approximately 40 ml of cement slurry was placed in such sample container. The sample container was subsequently attached to the tip of a glass rod and then placed into the VSM.

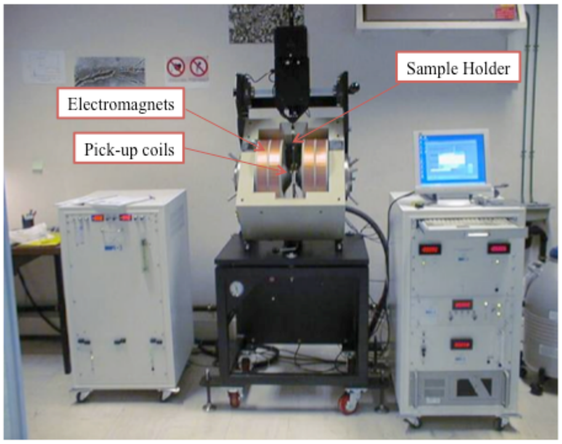

Figure 3.1 Picture of a Vibrating Sample Magnetometer (VSM) (CEA, 2010)

In this study, data was collected from the VSM between ±3 Oe (or ±0.3 mT) to obtain magnetization curve. Susceptibility (χ_m), a unit-less quantity, was measured as the slope of the magnetization curve between ±3 Oe (or ±0.3 mT). Based on the susceptibility (χ_m) of each sample measured from VSM, the relative magnetic permeability (μ_r) can be calculated by the definition:

$$\mu_r = 1 + \chi_m$$

where μ_r is the relative magnetic permeability of the material. The relative magnetic permeability μ_r, is the ratio of the magnetic permeability of a specific material to that of free space. The magnetic permeability of the free space is defined as the permeability constant, $\mu_0 = 4\pi \times 10^{-7}$ H·m^{-1}. Magnetic permeability is used to describe the capability of materials to be magnetized when placed in a magnetic field. Materials with higher relative permeability, for example, ferromagnetic materials, can present higher magnetization under a magnetic field (Ida, 2015).

3.3 FEMM SIMULATION

Finite Element Method Magnetics (FEMM) is a finite element program suitable for solving 2D planar and axisymmetric magnetic and electromagnetic problems. The Lua scripting language is integrated in the FEMM. Lua is the scripting engine used by FEMM to provide flexibility and freedom for users to easily build geometrical models and solve highly complicated problems. FEMM has a material library providing the magnetic properties of common materials for simulation. The magnetic properties (such as coercivity and relative magnetic permeability) of materials used in the simulation for this study are listed in Table 3.2. Coercivity is a property of magnetic materials, and is a measure of the materials' ability to resist demagnetization. It denotes the strength of an external magnetic field that is required to demagnetize the permanent magnet (Cullity and Graham 2009). FEMM was utilized to conduct simulations and plot magnetic field lines for all experimental setups, potential practical field setups, and for cement annulus monitoring. The figures of magnetic field distribution with flux density based on different colors were generated from the analysis results of FEMM simulations. These FEMM simulations played a crucial role in determining the shape and size of the permanent magnets used in this study. They were also useful in designing the experimental setups to ensure that the magnetic field was present in the required direction, with sufficient magnetic field strength in the area of interest.

Table 3.2 Properties of materials used in the FEMM simulation

Component	Material	Coercivity Hc (A/m)	Relative Permeability μr
Steel Casing	1018 Steel	0	530
Acrylic Pipe	Acrylic	0	1
Air	Air	0	1
Magnet Holder	PVC	0	1
Permanent Magnets	NdFeB 42	9.15x10^5	1.05

3.4 EXPERIMENTAL SETUP

3.4.1 Setup I: Pressure and Flow Prevention Seal

The first small-scale set up (schematic shown in Figure 3.2) was built to demonstrate that a MR-based fluid (either a drilling fluid, or a spacer fluid or a cement-based fluid) could withstand pressure applied to the fluid in the presence of an external magnetic field. This ability can be useful for many applications in well constructions. Throughout the life of the well, MR fluid can be used to avoid or remediate annular fluid flow and gas migration that compromise zonal isolation. For workover, remedial and abandonment operations, MR fluid can be used to form top-, bottom- or straddle packers with the applied magnetic field. These temporary magnetic packers can be removed after the operations when the applied magnetic field is removed. When used with a combination of Blowout Preventers (BOPs), with its instantaneous stiffening effect, an MR fluid can accelerate the formation of pressure isolation when closing the BOP elements.

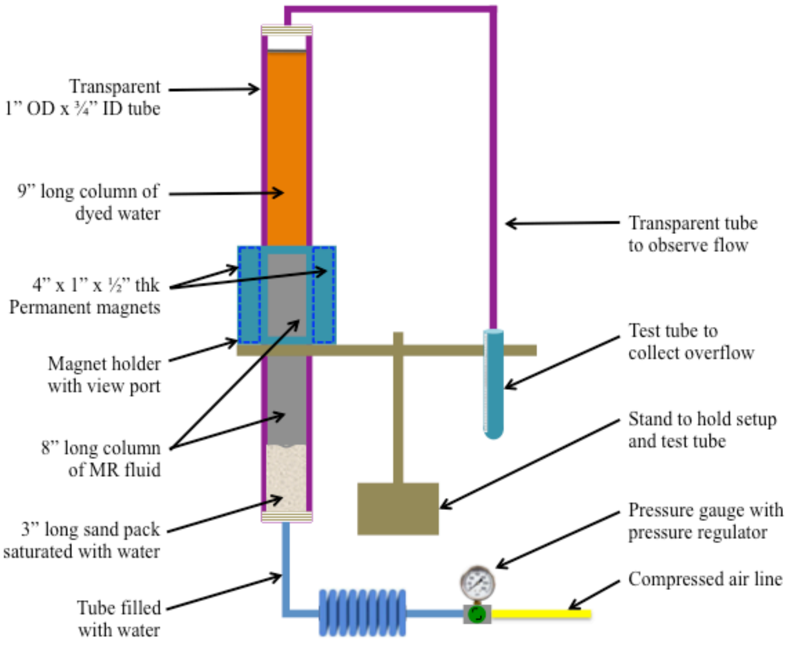

Figure 3.2 Schematic of setup I, demonstrating that in a presence of a magnetic field, a MR fluid can withstand pressure

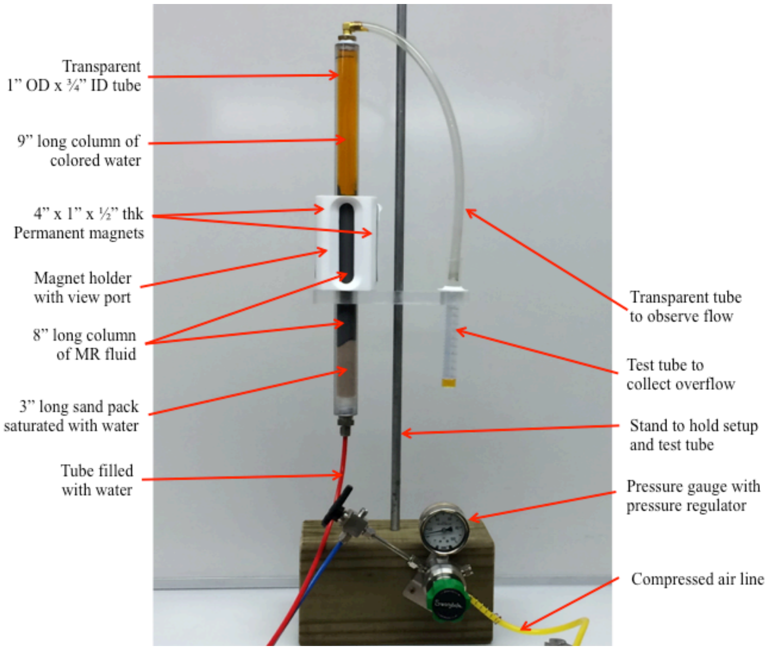

Figure 3.3 Photograph for experimental setup I

MR fluid (MR_X) was placed inside a 1” OD x ¾” ID acrylic tube. A 100-psi compressed air line was used to apply pressure to the system. A pressure regulator was used to slowly increase the pressure applied inside the tube. A ¼” tube filled with water was connected between the pressure regulator and the acrylic tube to simulate unexpected flow inside a well. A sand pack saturated with water was used to prevent back flow of the MR fluid (MR_X) prior to the application of magnetic field (or lowering of the permanent magnets into place). A column of dyed water was placed on top of the MR fluid column. When the pressure applied in the acrylic tube in the presence of a magnetic field exceeds the flow resistance of the MR fluid column, the MR fluid column becomes permeable and allows flow through it. This leads to a rise in the level of the colored fluid in the column. A test tube was placed downstream to collect the overflow of the colored fluid.

As shown in Figure 3.2, two 4 × 1 × ½” thick magnets (Type 1 from Table 3.1) were placed facing each other along their thicknesses to generate a magnetic field inside the clear acrylic tube (Figure 3.4). This configuration of the magnets ensures that the magnetic field lines in the tube are horizontal (see Figure 3.4). This is critical because the magnetic particles in a MR fluid will align along the direction of the magnetic field, and this arrangement of magnets reduces the vertical permeability of the MR fluid column.

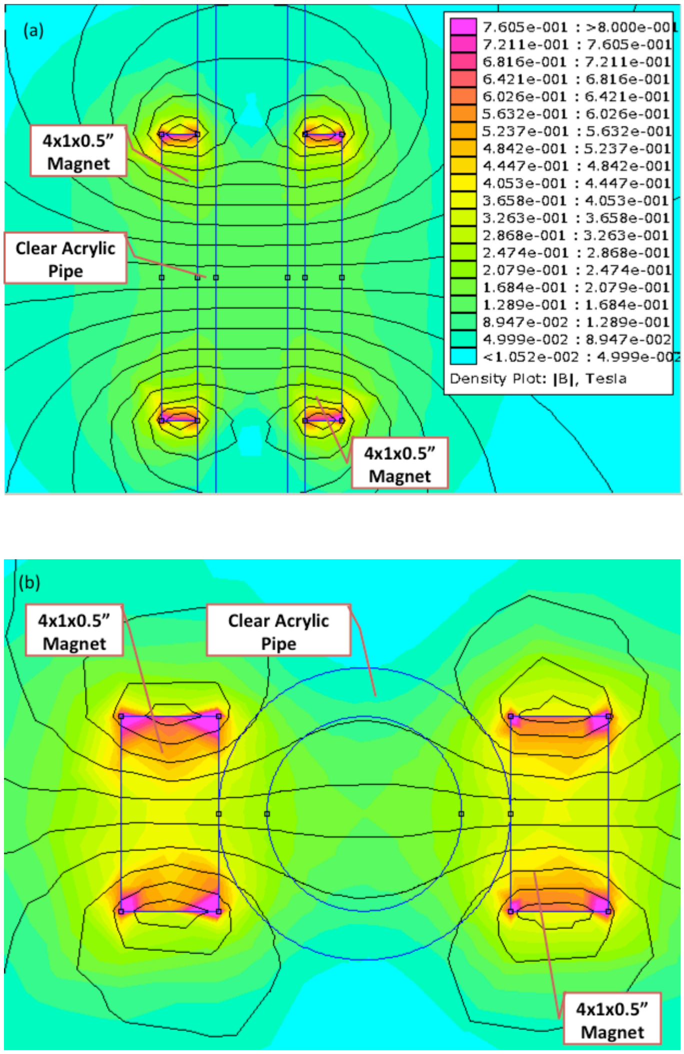

Figure 3.4 (a) Shows the magnetic field lines generated using FEMM along the vertical cross section of setup I. (b) Shows the magnetic field lines along the horizontal cross section. From both figures, it can be seen that by placing two magnets facing each other, magnetic field lines are generated perpendicular to the direction of flow.

3.4.2 Setup II: Displacement of Drilling Fluid

The purpose of the second experimental set up (schematic shown in Figure 3.5) is to demonstrate how a magnetic field can be used to influence the flow direction of MR fluids. This ability to direct flow is most beneficial when the casing is not centralized properly, resulting in the flow of cement slurry through the wider annular gap (as shown in Figure 2.3) to be easier and faster than that through the narrower gap, and thus displacement might lag behind and be incomplete in the narrower gap.

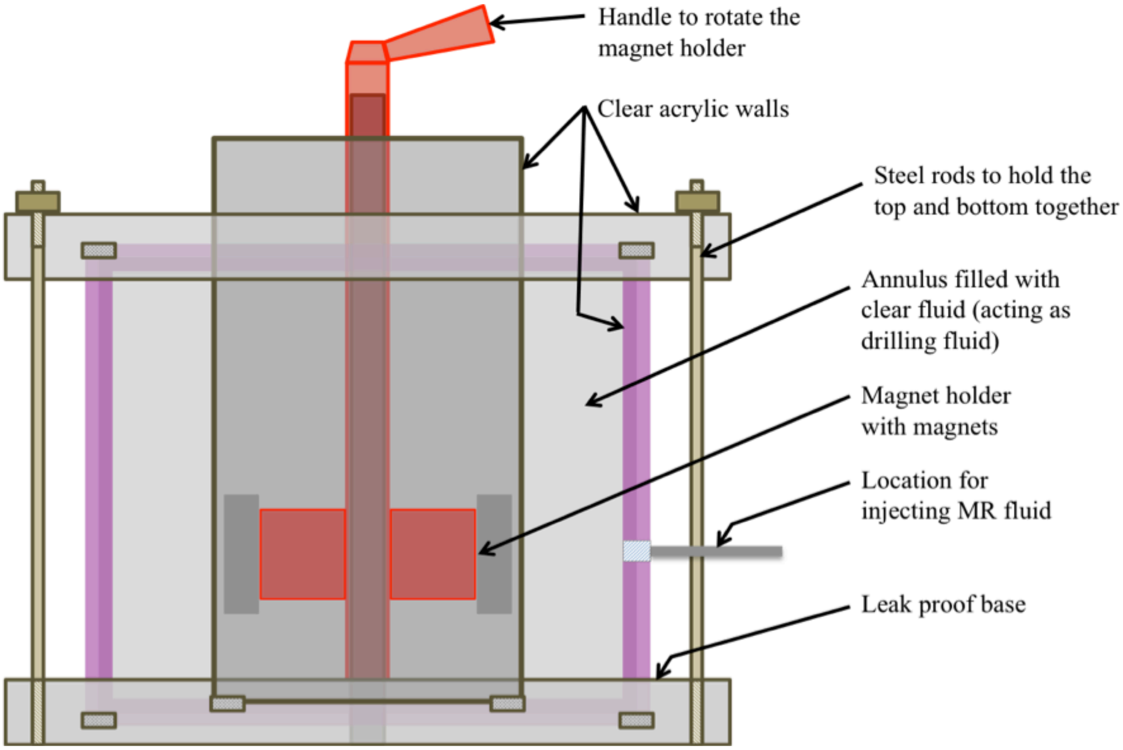

Figure 3.5 Schematic of setup II, demonstrating how a MR fluid can displace a drilling fluid in the presence of a magnetic field

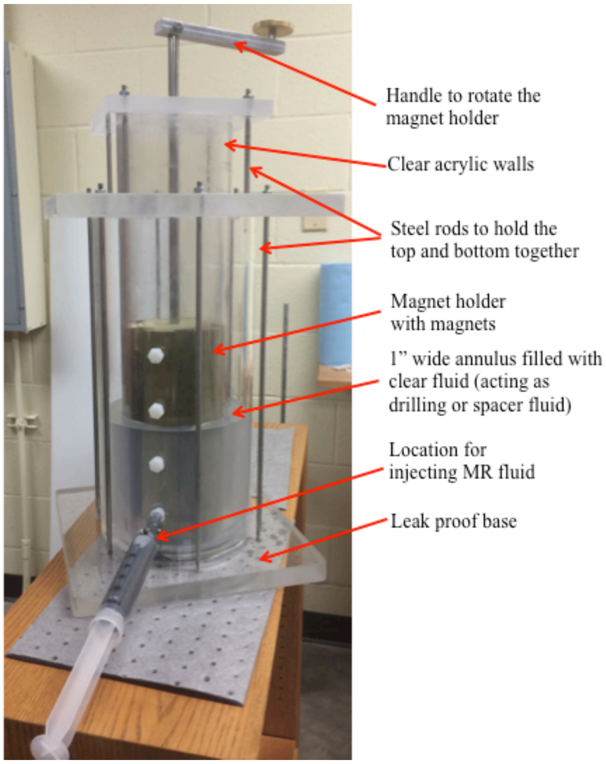

Figure 3.6 Photograph for experimental setup II

In this set up, a 5¾" OD × ¾" thick × 20" long clear acrylic pipe was used to simulate a casing string. An annulus was created by using 8¼" OD × ¾" thick x 16" long clear acrylic pipe to act as the boundary of a rock formation. The annulus was filled with WSR to act as a drilling or spacer fluid, and MR_X was used to act as a cement-based MR fluid. This experimental setup was designed to simulate displacement of WSR by MR_X in the presence of a magnetic field. Six 2 × 1 × ½" thick magnets (Type 2 from Table 3.1) were mounted with non-magnetic alloy screws onto a non-magnetic hexagonal block and placed inside the acrylic casing. Figure 6 shows the magnetic field lines that are generated in the annulus by placing the six magnets along a hexagon inside the casing. By offsetting the inner acrylic pipe, the case of a non-centralized casing (Figure 3.7 (b)) can be visualized. In both of the cases, the block containing the magnets can be rotated at a uniform speed to generate a “uniform” magnetic field in the entire annulus. For the arrangement shown in Figure 3.7 (a), the largest magnetic field strength in the cement annulus closest to the casing is 0.14 T, and the largest magnetic field strength closest to the formation is 0.07 T.

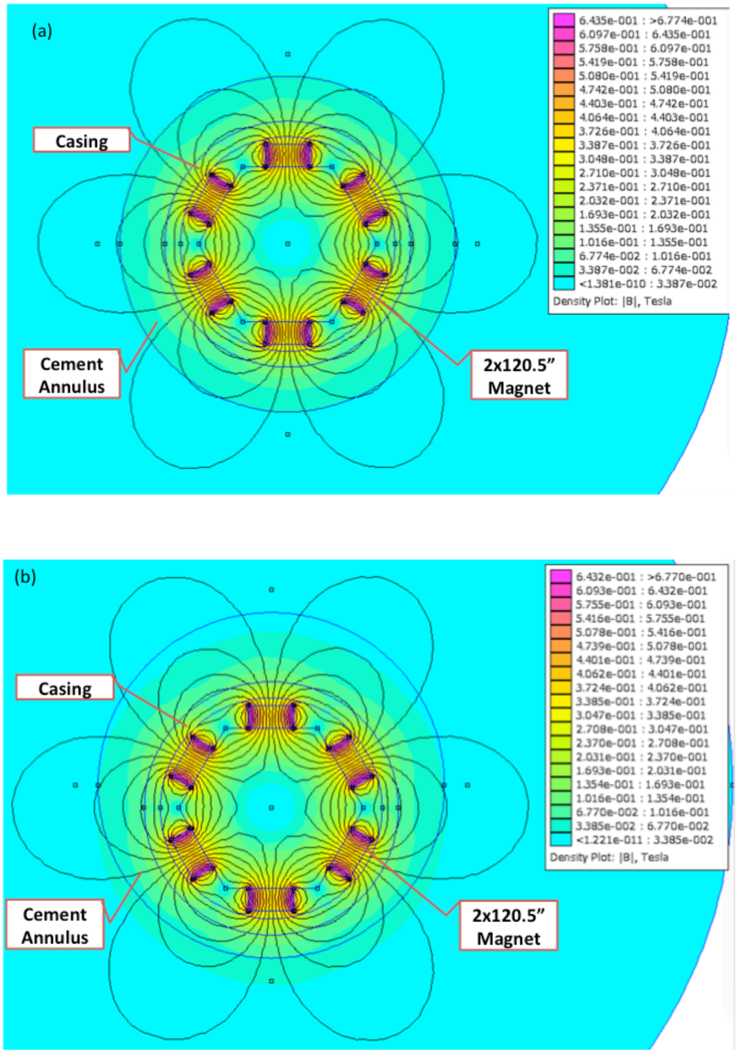

Figure 3.7 Magnetic field lines for set up II generated using FEMM simulation for the case of (a) centralized casing and (b) non-centralized casing

Chapter 4: RESULTS AND DISCUSSIONS

The experimental setups described in the previous chapter were used to conduct experiments to depict the ability of the MR fluid to act as a flow prevention seal as well as its ability to enhance cement displacement. This chapter provides observations of these experiments and discusses the importance of the observations. The simulations using FEMM on cement bond monitoring and voids detections were also conducted and the results are discussed in detail. In this chapter, both laboratory and simulation results are presented.[5]

4.1 MR FLUID AS FLOW PREVENTION SEAL

This section explains how a pressure and flow prevention seal can be applied in an annulus by using a MR fluid. Figure 4.1 shows a series of snapshots from a video that was shot during the experiment. As shown in Figure 4.1 (a), before applying the pressure into the system, the MR_X fluid column was held in place by the magnetic field generated from the two 4 × 1 × ½" permanent magnets in the magnet holder. The pressure regulator was opened slowly to increase the pressure in the column by 2 psi at 2-minute intervals. Both the dyed orange fluid column and the MR_X fluid column held steady until the pressure in the column increased to 12 psi (Figure 4.1 (a-b)). This experiment demonstrated that under the external magnetic field (ranging from 0.07 T to 0.17 T) provided by the Type 1 permanent magnet, the MR_X fluid column had sufficient yield strength, matrix impermeability to prevent flow of fluids and transmission of 12 psi pressure, effectively providing zonal isolation.

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[5] Nair, Sriramya D., Qian Wu, Mike Cowan, and Eric van Oort. 2015. "Cement Displacement and Pressure Control Using Magneto-Rheological Fluids." In proceedings of SPE/IADC Drilling Conference and Exhibition, London, U.K., 2015.

As the pressure was further increased, the level of the orange fluid in the column started to rise slowly, indicating a very low permeable MR_X fluid column above the applied 12 psi pressure (Figure 4.1 (c-d)). When the pressure was increased to 16 psi, the orange fluid began flowing and collecting in the test tube (Figure 4.1 (e-f)). At 20 psi, the MR_X fluid column began to move upward along with newly created flow paths inside the column, demonstrating how the strength of the external magnetic field could no longer hold the MR_X particles together and essentially the flow prevention seal was compromised (Figure 4.1 (g-h)). When the pressure was increased to 22 psi, the separation of MR_X fluid column was observed (see Figure 4.1. j) and the sand pack started to penetrate into the MR_X fluid column (see Figure 4.1i).

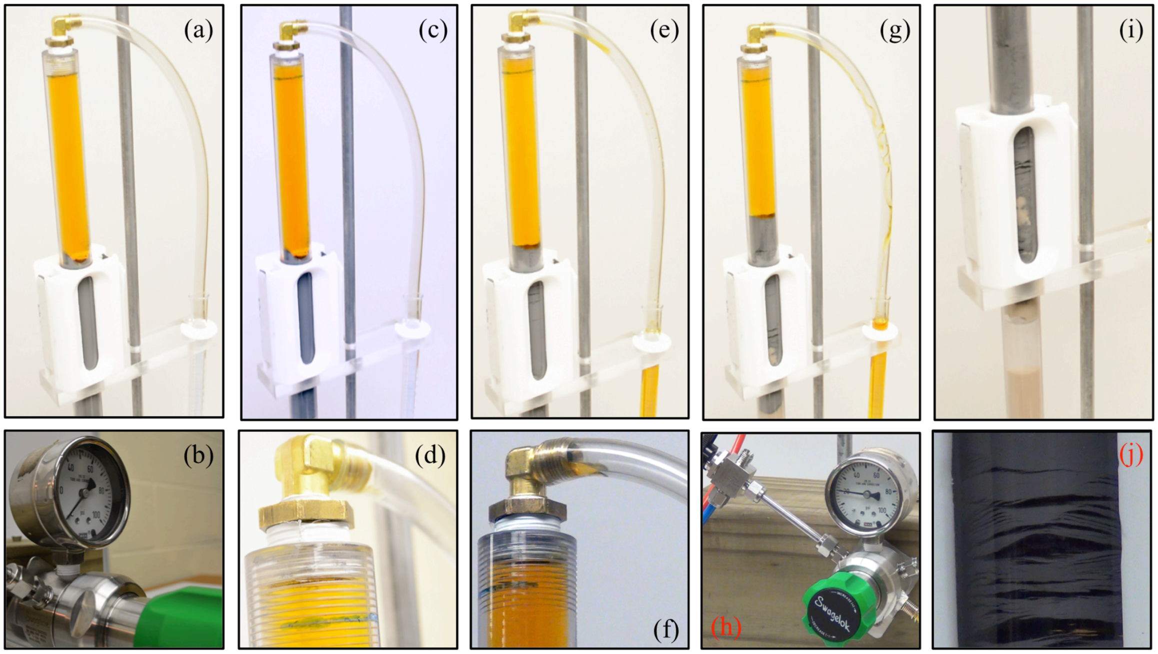

Figure 4.1 (a) and (b) Orange fluid level-indicated in blue ink on column. Between 0 and 12 psi, this level was held steady by applied magnetism; (c) and (d) When pressure increased above 12 psi, the orange fluid began flowing above the blue level indicator; (e) and (f) The orange fluid began flowing into the flexible tubing (16psi); (g) and (h) MR fluid column begins to push the orange fluid column (20psi); (i) and (j) The MR fluid column continuously moves up and begins to separate into different layers (22 psi).

It was found through the FEMM simulations (Figure 3.4) that the magnetic field strength inside the acrylic pipe varied from 0.07 to 0.17 T. The difference in magnetic field strength inside the acrylic tube can be visualized in Figure 3.4 (b) by noting the color difference inside the tube using the color scale provided in Figure 3.4 (a). These varying levels of magnetic field would generate a MR fluid column with different stiffnesses in different areas, which might lead to a gradient in the permeability of the system. It was shown by Nair and Ferron (2014) that by changing the applied magnetic field strength from 0.2 T to 0.4 T, the elastic component of the shear modulus (also known as storage modulus) increased by at least 1.5 times the value at 0.2 T for a MR cement-based fluid containing 4% CIP particles by volume of cement. Thus, a higher magnetic field strength would probably lead to a MR column of lower permeability. For future modifications, a more uniform field should be generated (possibly by using an electromagnet/rheostat setup) to reduce the impact of this gradient effect and to develop a stronger seal.

By controlling the location and path of the applied magnetic field, the magnetic fluids can be directed into pressure/fluid leak paths, thus creating a seal. Note that the effects of a magnetic field may persist even when the field strength is reduced or removed. Based on a cement rheological study (Nair 2013), it was shown that after removing or decreasing the strength of external magnetic field, the aligned magnetic particles retained a higher shear modulus compared to the cement slurry with same hydration time (and thus are still capable of providing a seal, although weaker than that formed with the existence of the magnetic field).

The magnetic field itself can be created by: (1) permanent magnets attached to either the inside or the outside of the casing through which treatment fluid will be pumped; (2) an electromagnetic field generator in a tool powered from an energy source on the ground or (3) an electromagnetic field generator attached to a down-hole motor/turbine,

The current set of experiments was dedicated to demonstrating a proof of concept, and not to develop optimized solutions that could already be applied in the field. Several factors can still be optimized to maximize the sealing capability of MR fluids, such as type of fluid (gas or liquid) to contain, length and width of the MR fluid column (e.g. simulating the behavior of a small channel / crack in cement; note that it will probably be much easier to contain flow in a small channel than a large surface-area column), applied magnetic field strength, concentration of magnetic particles, average particle size or particle size distribution of the magnetic particles in MR fluid, etc. Furthermore, it is possible to tailor external magnetic field to form an MR fluid column with higher permeability resistance and capability to hold higher pressures than what was achieved in this work. It is also possible to engineer the performance of an MR fluid is by optimizing the particle size distribution of the particles (both magnetic and nonmagnetic) of the MR fluid so that the particle packing efficiency enhances the magnetorheological effects (i.e. it would take lower concentration of magnetizable particles and/or lower magnetic field to create the required properties for the seal).

It is, therefore, useful to consider potential field applications for the technology (van Oort, Cowan, Nair and Ferron, 2014). A particularly interesting application for this technology would be to form a flow-seal using an MR fluid and an applied external magnetic field in the annulus above the top of cement (TOC). An MR fluid can be placed above TOC and activated by an external magnetic field either in anticipation of, or response to, gas and fluid migration in the annulus, thereby helping to mitigate sustained annular casing pressures. The MR fluid could be pumped directly ahead of the cement slurry for this particular purpose. It might even be possible by using a magnetic response from either the spacer, cement, or both, to help identify the placement of cement, the location of TOC and the quality of the cement bond (as discussed further below).

The combination of an MR fluid and an externally applied magnetic field may also be used to form a removable or temporary packer, by which it is possible to temporarily isolate sections of a wellbore during remedial/recompletion treatments or abandonment operations. The fluid or fluids may be placed in the wellbore below the treatment interval, above the treatment interval, or both above and below the treatment interval to provide a pressure barrier to contain or direct treatment fluids into a section or sections of the wellbore. A magnetic field can be applied to form a flow-resistant MR fluid column that will withstand pressure transmission and fluid flow. This is particularly applicable and effective where conventional wireline or tubular-conveyed bridge plugs or packers would have to be drilled out or are at high risk of being damaged during installation or retrieval, wherein their removal would render the wellbore unusable for future production.

Along these lines, it is also possible to envisage use of MR fluids in combination with blow-out preventers (BOPs) to either provide additional pressure sealing resistance or leak prevention capability, and to potentially reduce response time to arrest a kick. Note that it takes quite a bit of time to close BOP elements after a kick has been diagnosed (note that minimum response time of surface BOP's is specified in API-RP53 (2011), with closing system capable of closing each ram preventer within 30 sec., annular preventers <20" within 30 sec., and >=20" within 45 sec.), thereby allowing additional volume influx into the well until full shut-in has been established. Since the yield stress increase of a MR fluid upon application of magnetic field is instantaneous, it may be used to help establish immediate shut-in control until the BOP elements are fully closed.

4.2 MR FLUID FOR ENHANCED DISPLACEMENT OF CEMENT

By using set up II (schematic shown in Figure 3.5), in the case of a perfectly centralized casing, the annulus was filled with WSR fluid and then MR_X magnetic fluid was injected into the annulus through a side port. In the absence of a magnetic field, it was found that the injected magnetic fluid would just flow down to the bottom of the setup because of its higher viscosity and density. By slowly rotating the magnet holder while continuously injecting MR_X fluid, it was observed that the fluid was held in place by the magnetic field and no longer settled, whereas the particles became clearly aligned along the direction of the magnetic field (Figure 4.2). With continued rotation of the magnet holder, the magnetic particles were actively directed along the magnetic flux lines (see Figure 4.3).

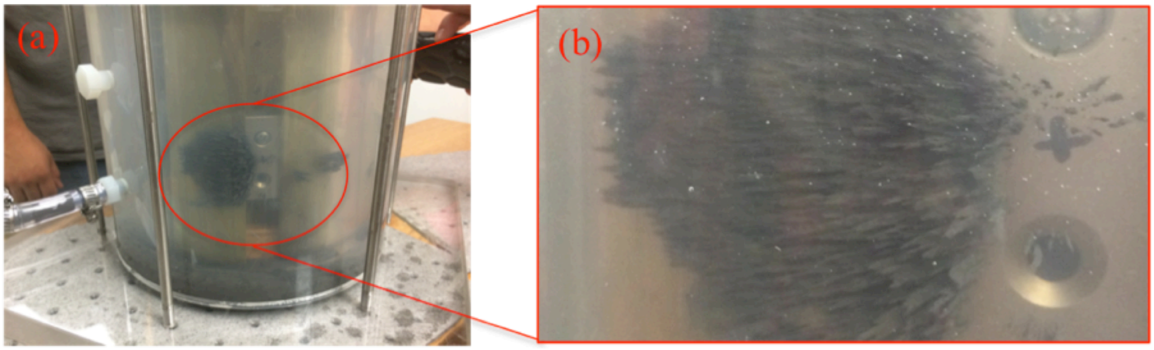

Figure 4.2 (a) Displacement of WSR fluid by MR_X fluid in the presence of magnetic field. (b) Shows an enlarged picture of the alignment of the magnetic particles present in MR_X fluid in the direction of the magnetic field lines of the permanent magnets.

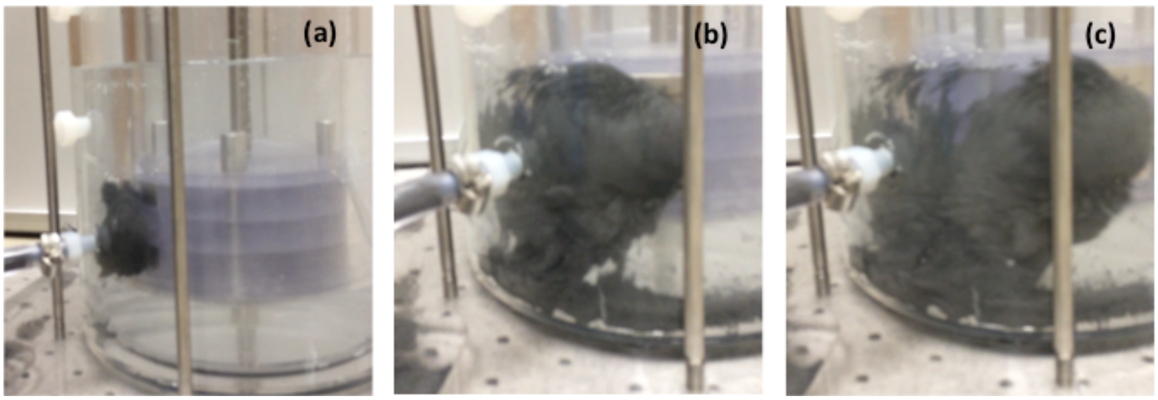

Figure 4.3 (a) Injection of MR fluid into the setup II; (b) and (c) Magnetic particles directed by slowly rotating the permenant magnents

In Figure 4.4, a section of the annulus is filled with WSR fluid (simulating undisplaced drilling fluid), and another section is filled with MR_X fluid (simulating cement-based MR fluid). By continuously rotating the block containing the magnets, it can be ensured that cement is present in the entire annulus. To apply the concept shown in Figure 4.4 in the field, a tool with the capability of applying a magnetic field in the annulus will have to be lowered inside the casing and be rotated for a certain period of time to ensure complete intermixing of the drilling fluid and the cement. It has been shown by Aughenbaugh et al. (2014) that when cement is contaminated with synthetic based drilling fluid, the compressive strength of hardened cement drops significantly. Thus, for practical purposes (see Figure 4.5) further explained in the next paragraph, it might be beneficial to strategically place permanent magnets on the outside of the casing, or magnetize the casing itself, to ensure that the drilling fluid is completely displaced during the cementing operation.

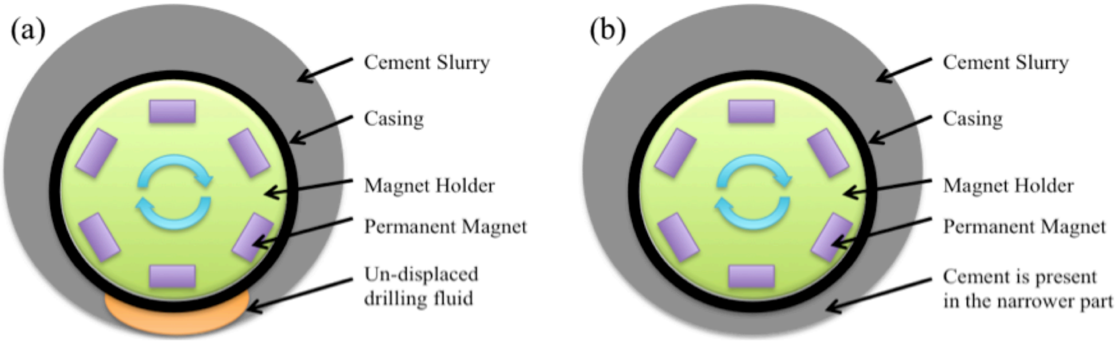

Figure 4.4 (a) Un-displaced drilling fluid (WSR fluid) channel during cementing process (b) Cement slurry (MR _X fluid) in the entire annulus due to application of a magnetic field, use of cement-based MR fluid, and possible rotation of the magnets or rotation of casing with fixed magnets, as indicated by the blue arrows.

Differential field strength may be used to optimize re-direction of fluid flow into narrower gaps in the annulus. For example, a lower strength magnetic field may be applied to the wider gap to slightly increase viscosity and frictional pressure of the MR cement-based fluid. This will help prevent fracturing of the formation. Simultaneously, a higher strength magnetic field can be applied to the narrower gap to direct flow at lower differential frictional pressures. Optimally, a rotating magnetic field may be used to create a radial circulation of fluid around the entire circumference of the casing. This application can be seen as a potential alternative or augmentation to rotation of the casing while cementing, which is known to be highly beneficial to proper cement displacement (Nelson and Guillot, 2006). The added advantage of the MR method is that through the influence of the magnetic field, which can even hold cement in place (see Figure 4.4) on the outside of the casing, the MR cement slurry is actively dragged around the casing towards the narrower annular gap, thus eliminating the mud channel.

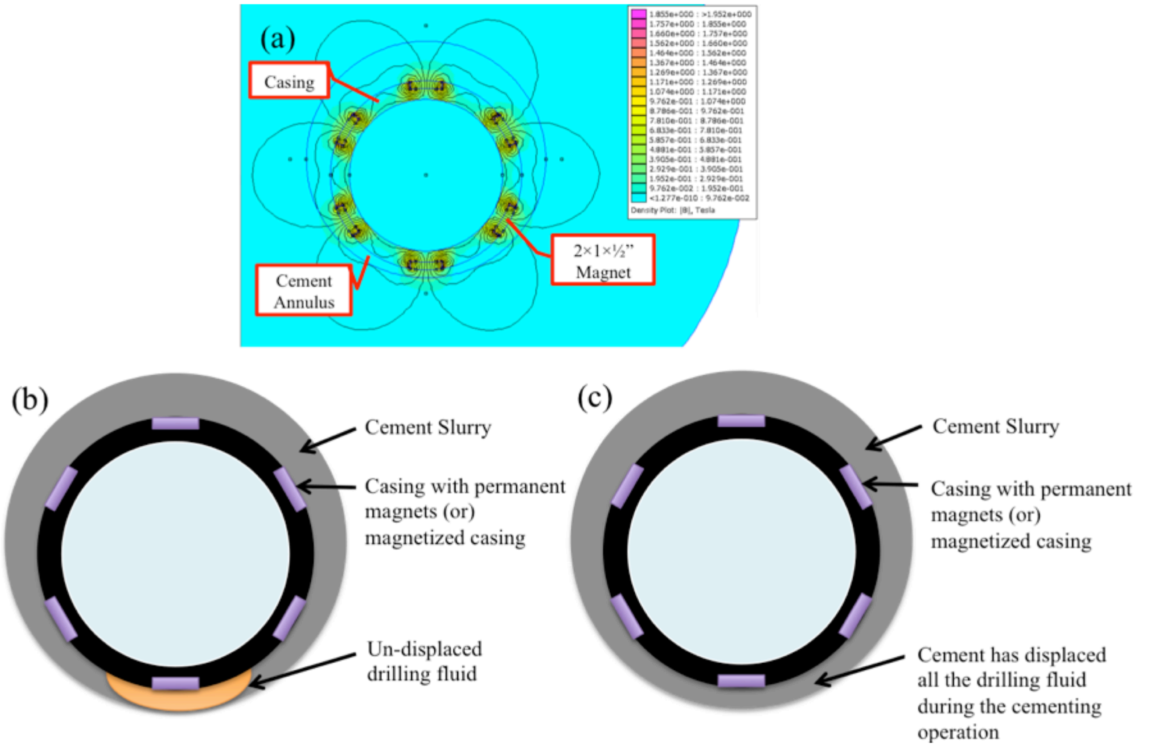

Figure 4.5 (a) Magnetic field lines generated using FEMM simulations (b-c) Drilling fluid or spacer fluid can be displaced during the cementing operation without having to lower a tool that can generate magnetic field in the annulus.

Typically, higher viscosity fluids more effectively displace lower viscosity fluids. More specifically, the frictional pressure generated by the displacing fluid (spacer and cement) should be higher than the frictional pressure of the displaced fluid (drilling fluid). The frictional pressure generated by each fluid is a function of the annular geometry, rheological properties and flow rates. Wellbore irregularities such as changes in wellbore diameters along the length of the wellbore and shape (oval rather than circular) may require different rheological and frictional pressure relationships to maintain effectiveness. Rheological properties of fluids change at different rates depending on temperature changes in a wellbore. Furthermore, some polymers lose their effectiveness above certain temperatures - no matter the concentration. Therefore, obtaining rheological and frictional pressure relationships that support optimum efficiency for the displacement process may not be possible due to thermal reduction in viscosity of the fluids. But, the displacement might be more efficient through use of cement-based or spacer-based MR fluid to control their rheological properties in real time with applied magnetic fields.

4.3 CEMENT ANNULUS EVALUATION AND MONITORING

The possibility of using the cement-based MR fluid as a sensing medium to achieve non-destructive, non-disturbed and long-term health monitoring of cement bonds has been evaluated. The de-bonding between casing and cement or cement and formation leads to the formation of micro annuli, which creates pathways for fluid communication and gas migration. Real time monitoring of the cement bond would identify the presence of such annuli and help manage them.

4.3.1 Relative Permeability of MR Cement

As previously mentioned, a key parameter for observation is the magnetic relative permeability of materials. As described previously in the VSM section, the magnetic relative permeability (a unitless quantity) is defined as $\mu r =1+ \chi m$, where the value of susceptibility (χm) is obtained from the VSM results. Magnetic field lines will preferentially flow through a material that has a higher relative permeability. This means that for the same externally applied magnetic field strength, the magnetic field strength detected in the annulus will be higher if the relative permeability is also higher. In general, the magnetic relative permeability of non-magnetic materials is close to 1. For example, the magnetic relative permeability of air is 1. As shown in Table 4.1, the permeability of neat cement paste and Pierre shale are also close to 1.

Adding CIP particles into cement slurry increases its magnetic relative permeability. The hypothesis is that the difference in relative permeability between air or shale and cement with CIP can be utilized to detect defects like de-bonding, voids and channeling in the cement annulus. This study focuses on the de-bonding between the casing and cement annulus. When de-bonding occurs, an air gap is produced, creating a path for fluid or gas flow. In this gap, the relative magnetic permeability decreases from the value of the cement with CIP to a value of 1. The gap creates a path that is more difficult for a magnetic field to go through, thus lowering the strength of magnetic field. The magnetic relative permeabilities of different cement slurries with varying dosages of CIP particles are shown Table 4.1. The relative permeability of cement paste without any magnetic particles determined in this study is consistent with values reported in literature (McEnroe, 1998).

Table 4.1 Magnetic relative permeability of cement slurries with CIP sample obtained from VSM measurement

Sample	Relative Permeability (μ_r)	
	1 hour	7 days
Neat paste (0CIP)	1.002	-
4CIP	1.06	1.10
20CIP	1.50	1.40
30CIP	1.74	1.40

The magnetic relative permeability of cement paste, with or without CIP, does not experience significant change after hardening for 7 days. As it is shown in Table 4.1, the relative permeability of samples with 20% and 30% CIP by volume decreases when comparing the values measured after curing for 1 hour and 7 days. In other literature, the susceptibility values of cement paste were found to increase for the first 2 hours, which was explained by the early formation of an aluminoferrite hydrate that is rich in iron. After 1-week hydration, the susceptibility values were found to decrease and can be explained by the condensing and thickening of cement paste (Gopalakrishnan et al., 2012). Since the relative permeability is calculated from the magnetic susceptibility by $\mu_r = 1 + \chi_m$, the decrease of relative permeability values of MR cement-based fluid samples in this study might be also explained by the effect of cement hydration.

In Table 4.1, one hour after the cement-based MR fluid is prepared, by increasing the percentage of CIP from 4% to 30% by volume, the value of relative permeability increases by 70%. However, this increase in value is not very significant if the relative permeability of 30CIP is compared to that of a steel casing measured at 530 (Table 3.2). It is not practical to further increase the dosage of CIP magnetic particles, as this might influence the quality and the strength of the cement. Thus, additional study is required to verify whether or not the relative magnetic permeability of cement paste can be improved through means other than increasing the volume dosage of the magnetic particles.

4.3.2 Cement Bond Monitoring

For carbon steel casing, if permanent magnets were to be placed inside the casing, most of the magnetic field lines would pass through the casing (because of its high relative magnetic permeability) and very few magnetic field lines would pass through the cement annulus. With a higher value of relative permeability than that of air or other non-magnetic materials, carbon steel casing provides an easier path for magnetic field to travel between the magnet’s poles. This physical nature of carbon steel causes the casing to act as a “magnetic shield” to “hold” the flux lines inside it, preventing penetration of the flux lines into the cement annulus (as shown in Figure 4.6), unless the steel becomes saturated with magnetic field. Saturating the carbon steel casing requires a considerable amount of applied external magnetic field.

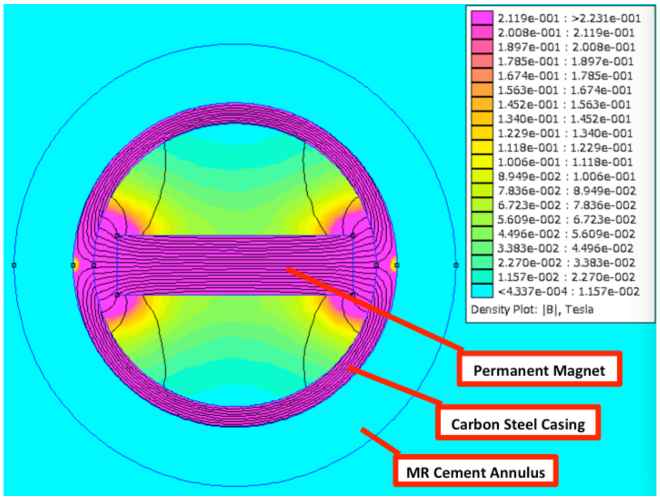

Figure 4.6 Carbon steel casing provides an easier path for magnetic field to travel between the magnet’s poles

In this study, it was assumed that the casing can be magnetized as a two-pole magnet (one pole at point A and another pole diagonally opposite to A, as shown in Figure 4.7(a)). A section of casing can also be made out of tube-shaped permanent magnets that are diametrically magnetized (similar to the permanent magnets shown in Figure 4.8). It was also assumed that the magnetic field sensors could be installed in the annulus and on the outside of casing to measure the changes in the magnetic field strength. From Figure 4.7(a), it can be seen that magnetic field lines now pass through the cement annulus. In this FEMM simulation, the most severe case of microannulus, which encircle the entire casing circumference, was considered and modeled. The FEMM simulation was used to assess how the magnetic field distribution in the annulus can be affected by the size of the microannulus. The enlargement of a microannulus was assumed to be uniform in all directions. As shown in Figure 4.7 (b), with a microannulus between the casing and cement sheath, there is a distortion of the magnetic field lines when compared to those of Figure 4.7 (a). Magnetic field strength values at Point A (0°), Point B (45°), and Point C (90°) were monitored during the enlargement of the de-bonding between the casing and the cement sheath. From no de-bonding to 0.3-inch gap, the magnetic field strength decreases by 100 Gauss at point A; the magnetic field decreases by 500 Gauss at point B, while the magnetic field decreases by 50 Gauss at point C. By measuring the changes in the magnetic field strength at different points around the casing, it should therefore be possible to observe the distortion of magnetic field lines due to de-bonding between the casing and cement sheath.

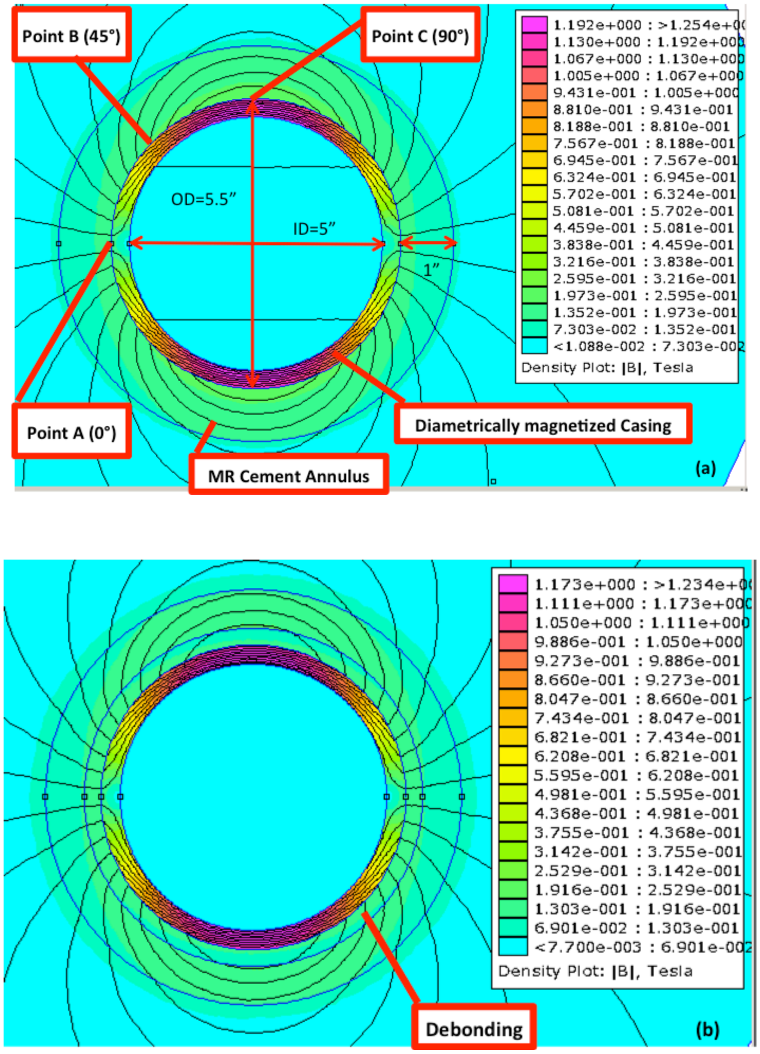

Figure 4.7 (a) Dimension of well model used for FEMM simulation along with the magnetic field lines for the case of a magnetized casing; (b) The distortion of magnetic field lines when there is a 0.3 in. de-bonding between the casing and cement annulus.

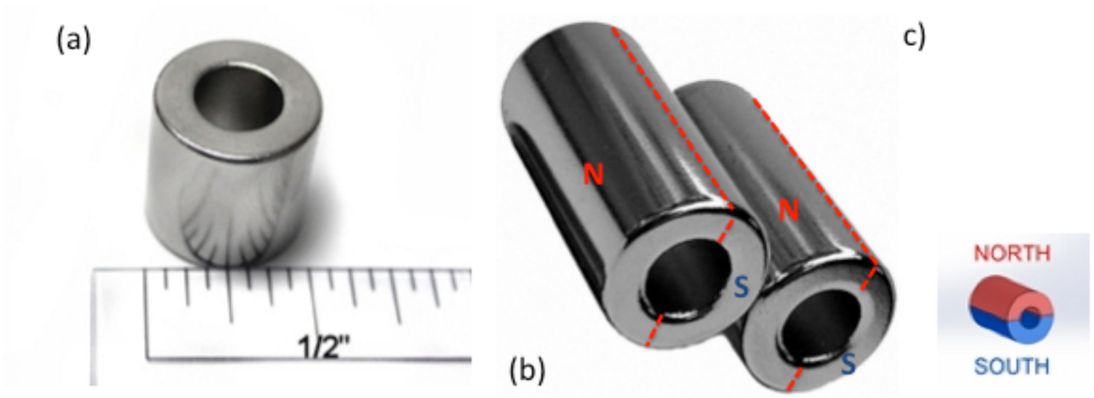

Figure 4.8 (a) and (b) Tube-shaped diametrically magnetized permanent magnet and its dimensions; (c) Magnetic field direction of tube-shaped permanent magnet (AMAZING MAGNETS, LLC, APEX MAGNETS, LLC)

To optimize the number of sensors to be installed on the casing, several key points were evaluated in this simulation model. The variation of magnetic field at point A, B and C due to the increasing size of the gap was recorded as shown in Figure 4.9. Since magnetic field is not uniform (see Figure 4.7), as the size of the de-bonded microannulus increases, a decreasing trend in magnetic field strength can be observed at point A and point C (Figure 4.9 (a) and (c)), but it is difficult to draw a significant relationship between the magnetic field strength and the size of gap. At point B, there is a significant decrease in magnetic field from no de-bonding to some de-bonding (Figure 4.9 (b)) while the magnetic field changes slightly as the width of microannulus increases from 0.01 inches to 0.3 inches. With four sensors installed at point B (45°) and symmetric points (135°, 225°, and 315°) on the casing, it is possible to detect whether or not there is a microannulus as shown in Figure 4.7.

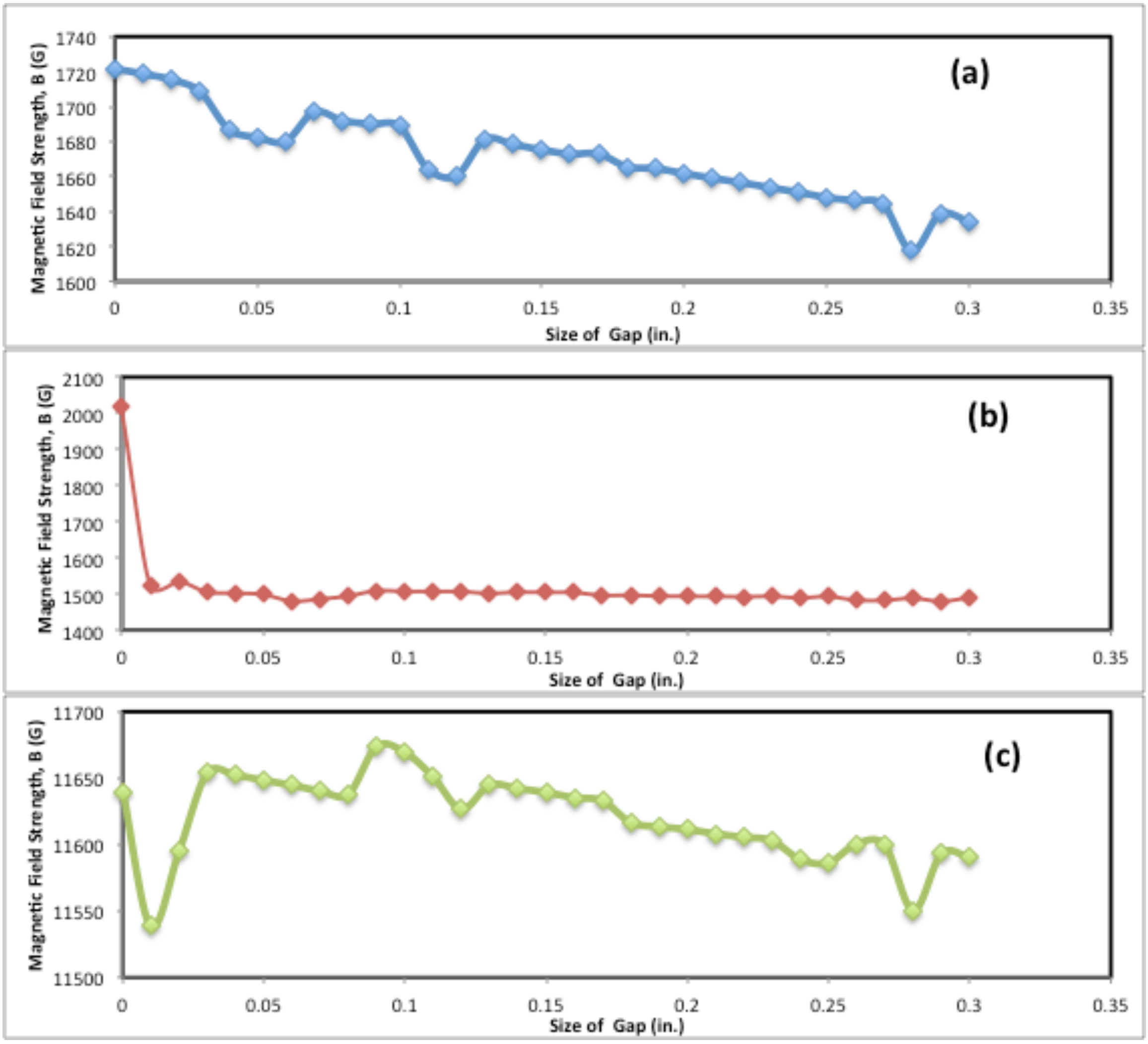

Figure 4.9 Magnetic field strength vs. size of gap (microannulus that encircled the entire casing circumference) at (a) point A,(b) point B, and (c) point C

4.3.3 Voids and Channels Detection in Cement Annulus

In this study, the same simulation model was used with the assumption that the casing was diametrically magnetized (Figure 4.7 (a)). The feasibility of using an MR cement as a medium for voids and channels detection in the annulus was studied using the FEMM simulation tool. It shows the potential to be applied both in the cementing process and during the life term of the well. Before a cementing job, a model can be built to estimate the magnetic field distribution and values in the cement annulus when there is 100% displacement efficiency (Figure 4.7(a)). After the displacement of drilling fluid by cement, the magnetic field strength in the cement annulus can be measured by the magnetic field sensors on the casing and then compared with the simulation values to evaluate the efficiency of displacement. During the lifetime of the oil or gas well, the presence of voids or channels in the cement annulus can also be detected by monitoring the changes in the magnetic field. Figure 4.10 shows a simple example of this idea. In Figure 4.10, the strength of magnetic field is shown in gray scale, in which the darker color represents higher magnetic field strength than a lighter color. The portion of the annulus where there was no MR cement in Figure 4. 8 (b) and (c) has a lighter color, which represents lower magnetic field strength, compared to the same locations in Figure 4.10 (a). By measuring magnetic field changes at different points around the casing, it should therefore be possible to observe the changes of magnetic field distribution due to the presence of voids or channels in the annulus. For example, magnetic field strength at Point A (0°) was monitored during the enlarging of the voids in the annulus. From Figure 4.10 (a) to (b), the magnetic field at Point A increases by approximately 120 G; from Figure 4.10 (b) to (c), the magnetic field at Point A increases by approximately 230 G. Since the magnetic field distribution is not uniform in the annulus, the magnetic field change at specific points due to increasing percentage of annulus without MR cement did not show a simple linear relationship as expected. Quantitative analysis is required to explore the relationship between the enlarging of voids in the annulus and changes of magnetic field. Also, further study can be conducted in 3-D modeling and simulation to evaluate the possibility to differentiate the size of the voids or channels. Further study is required to find effective ways of magnetizing the casing and to alter the location of the poles in real time to better analyze information from all the different azimuths in the annulus.

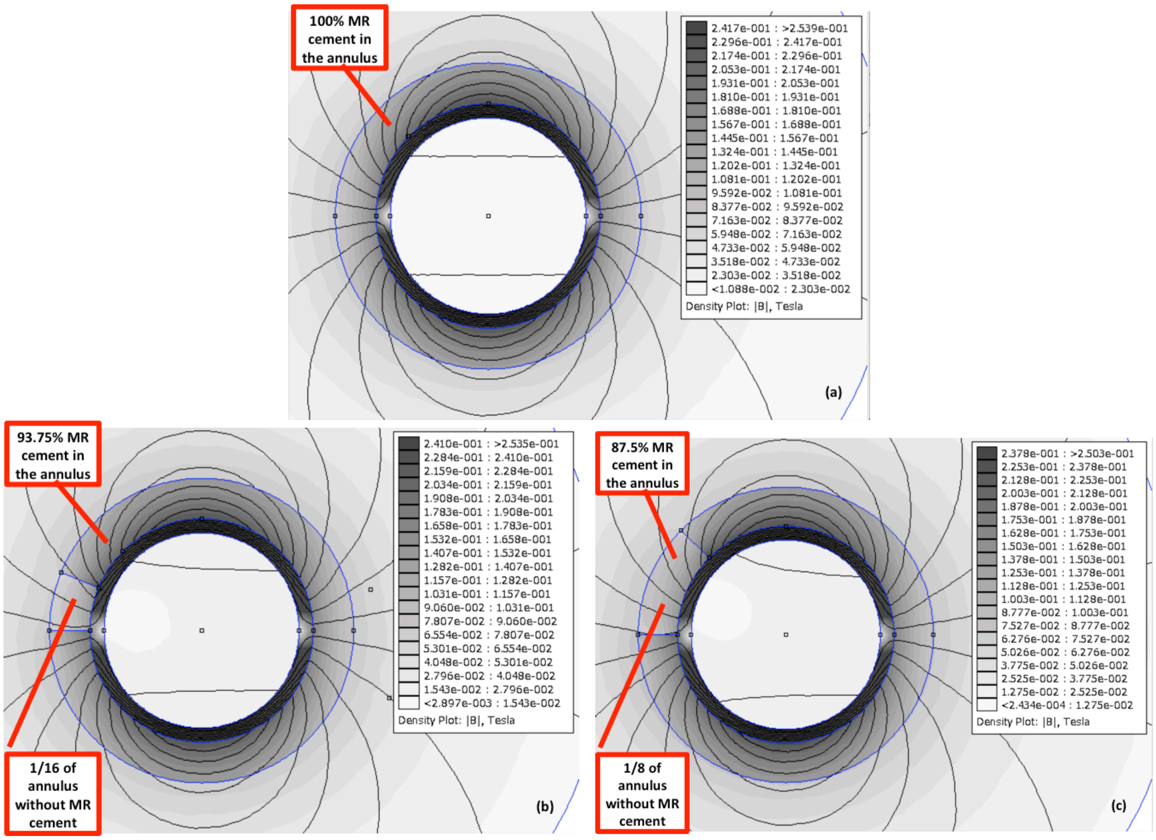

Figure 4.10 Density plots of magnetic field for (a) 100%,(b) 93.75%,and (c) 87.5% MR cement in the annulus

Chapter 5: CONCLUSION AND FUTURE WORK

5.1 CONCLUSIONS

In this study, it has been shown that MR fluids can benefit well construction in a variety of different ways.

First, MR fluids can be applied for a large range of differential pressure or flow isolation purposes. The preliminary study presents the capabilities of MR fluids to hold differential pressure. With certain improvement, interesting field applications can be explored in the following aspects:

- MR fluids could be applied to prevent fluid and gas migration in the annulus, which could compromise zonal isolation. This functionality can be applied throughout the life of the well. For example, it can be applied during production when the cement bonding is compromised by fluctuations of pressure and/or temperature.
- MR fluids could be used as top-,bottom-, or straddle packers, which can be the alternative of wireline or tubular-conveyed packers and isolation tools used in work-over, remedial and abandonment operations.
- MR fluids could be used in combination with BOPs to enhance pressure control, improve leak resistance and/or reduce response time for closing BOPs.

Secondly, MR spacer and cement could be applied to enhance the displacement efficiency. MR fluids can be actively directing and/or their viscosity and yield stress can be tailored to the targeted application with an applied magnetic field. This could be particularly beneficial for the displacement of mud when the casing is not centralized or casing rotation is not a possible option. By strategic magnet installation or magnet rotation, MR fluids may be guided to fill the annular spaces where they would usually not flow into without additional operations, such as the low side of the hole with eccentric casing. Therefore, MR fluids could be helpful in this way to minimize the mud channels and reduce the risk of mud contamination in cement annulus, which might compromise compressive strength development of cement.

Last but not least, MR fluids could also be used as a sensing medium in cement sheath health monitoring. Since the magnetic response of cement can be affected by the flaws, cracks and channels, it may be possible to use cement-based MR fluid to achieve non-destructive and long-term health monitoring of cement in the annulus. However, one of the big challenges is to overcome the effect of the casing with large magnetic permeability in order to achieve the magnetic sensing. Preliminary studies show it is possible to observe MR cement response if the casing can be magnetized.

5.2 FUTURE WORK

A few recommendations for future work on this study are listed as follows:

1. Improve the ability of MR fluids for the application of pressure and flow prevention seals. For experimental setup I, the permanent magnets can be replaced by the electromagnets to control the presence of magnetic field. In this way, it's possible to demonstrate flow prevention with the instantaneous stiffening effect of MR fluids with the on and off feature of an electromagnet. Experimental setup I is a small-scale model. A larger scale model can be constructed with a stronger and more uniform magnetic field to hold higher pressures. The relationships between the strength of magnetic field supplied, MR fluids used, and maximum pressure to be held should be studied further to properly design the device with the consideration of electricity supply that can be practically applied in the industry.

2. Optimize the methods to supply manageable and sufficient magnetic field in the oil and gas well for cement displacement and monitoring. In this study, different ways to provide magnetic field for application of MR fluids are presented, but each of them presents challenges in different aspects.

- Use downhole tool installed with permanent magnets inside the casing as shown in Figure 4.3 for experimental setup II. Further study should be focused on both the feasibility of using electromagnets instead of permanent magnets, as well as using casing made of non-magnetic materials to avoid the “magnetic shield” effect of carbon casing.
- Study the feasibility of installing permanent magnets outside the casing as shown in Figure 4.4 for cement displacement application using MR fluids.
- Magnetize the casing. Different magnetization methods need to be explored to find effective ways to magnetize the casing such as Halbach magnetization.
- Use tube-shaped diametrically magnetized permanent magnets as a section of casing string. The feasibility of installing large tube-shaped permanent magnets needs to be considered.

3. Explore MR cement-based fluid recipes to improve their relative magnetic permeability by changing types and/or dosage of magnetic particles.
4. For cement bond monitoring and voids detection, more focus is required on the design, installation, arrangement, and signal transmission of the magnetic field sensors.
5. The influence of applying magnetic field on the daily operations of an oil and gas well during construction or production needs to be explored in detail.

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