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**DESIGN AND CONSTRUCTION OF A MAGNETO-RHEOMETER  
TO DETERMINE THE RHEOLOGICAL PROPERTIES  
OF MAGNETORHEOLOGICAL FLUIDS  
FOR USE IN DRILLING APPLICATIONS**

**1. INTRODUCTION**

Worldwide demand for energy continues to increase at high rates, so drilling in deep depths is inevitable thus encountering adverse conditions of pressures and temperatures (HPHT drilling). The most common problems of HPHT drilling include poor hole cleaning, high pressure losses, loss circulation zones, fluid gelation, reservoir fluid invasions. Since HPHT drilling is expensive, the right choice of drilling fluids requires careful evaluation to successfully handle the challenges presenting (Kelessidis, 2009). Drilling industry has resulted in a range of drilling fluids, water based or oil based, containing additives such as bentonite or polymers which are used in difficult drilling conditions. The main problem of these drilling fluids is the thermal instability and the lack of flexibility to change their rheological properties in critical conditions (Kelessidis *et al.* 2007a, Kelessidis *et al.* 2007b). Industry is searching for flexible drilling fluids with adjustable parameters can be used in these wells. So there is a great need to develop new flexible fluids, compatible with the different rock formations and durable in high temperatures and pressures. Such fluids can be Magnetorheological fluids. The advantage of these fluids is that they have tunable rheological properties and can be used in adverse conditions.

**2. MAGNETORHEOLOGICAL FLUIDS**

Magnetic suspensions are fluids which exhibit a rapid and large reversible change in their rheological properties under the application of an external magnetic field. These fluids

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were discovered by Rainbow (1948) and have been used for more than 40 years (Jha and Jain, 2009).

They can be divided in two categories: a) Ferrofluids, which are composed of ferro-magnetic or ferromagnetic nanoparticles which are dispersed in a non- magnetic liquid carrier and b) Magnetorheological fluids (MR fluids), which are composed of meso-scale ferromagnetic or ferromagnetic particles (1–10  $\mu\text{m}$ ) in a non-magnetic carrier fluid (López *et al.*, 2006).

The selection of MR materials is limited in several magnetizable elements and alloys but the most common material is carbonyl iron due to its high magnetic permeability (Wang and Gordaninejad, 2006). Usually MR fluids contain a volume concentration of magnetic particles between 20 and 40% (Bica, 2006).

Due to the large density of solid particles in comparison to the density of the liquid carriers, MR fluids suffer from sedimentation. Three different approaches have been made to overcome this problem.

The first is to increase the viscosity of the carrier fluid so as the particles settle down slowly or no longer settle. Such fluids are greases, polymer gels or elastomers.

Another approach is to use nanoparticles (ferrofluids) which are more stable. The drawback of the ferrofluids is that they don't exhibit high yield stresses.

Lastly, different additives such as fibrous carbon or silica can be used in order to increase the density of the carrier fluid (Yang *et al.*, 2009).

When no magnetic field is induced MR fluids behave like Newtonian fluids. When external magnetic field ( $H$ ) is applied, they exhibit high yield stress (Genç and Phulé, 2002). This happens because the magnetic particles act like dipoles and they form columns, chains or more complex structures aligned with the field direction. This causes the MR fluid to exhibit semisolid behavior. The response time of this transition is 10–20 msec. At low applied fields the yield stress is proportional to magnetic density squared ( $H_0^2$ ). As the applied field increases the magnetic particles are saturated and the yield stress is proportional to the magnetic density ( $H_0^{3/2}$ ). When the particles are completely saturated, the yield stress becomes independent (Jun *et al.* 2005).

The most common model used to describe the rheological behavior of MR fluids is the Bingham plastic model (Jun *et al.* 2005, Jha and Jain 2009, López *et al.* 2006, López *et al.* 2008) which is given by the following equation:

$$\begin{cases} \tau = \tau_y + \mu_p \cdot \dot{\gamma}, & \text{for } \tau \geq \tau_y \\ \tau = 0, & \text{for } \tau \leq \tau_y \end{cases} \quad (1)$$

Where  $\tau$  is the shear stress,  $\dot{\gamma}$  is the shear rate,  $\tau_y$  is the yield stress and  $\mu_p$  is the plastic viscosity. The plastic viscosity of the medium mostly depends on the carrier fluid. Ginder

(1998) reported, that MR fluids also exhibit a shear thinning behavior and used Herschel Bulkley model to describe them, where the equation is given by

$$\tau = \tau_y + K \cdot \dot{\gamma}^n \tag{2}$$

where  $\tau_y$  is the yield stress,  $K$  is the flow consistency index, and  $n$  is the flow behavior index.

### 3. MAGNETORHEOMETER SETUP

Several different experimental setups have been investigated and devised in order to measure the rheological properties of MR fluids. Laun *et al.* (1996) and Ginder *et al.* (1996) designed concentric cylinder rheometers. The first ones used various magnetic field arrangements while Ginder *et al.* achieved flux densities over 1 Tesla. Laun *et al.* also designed a capillary rheometer. Lamaire and Bossis (1991), Li *et al.* (1999) and Genç and Phulé (2002) used parallel plate rheometers. Tang and Conrad (1995) have developed a sliding plate rheometer. Felt *et al.* (1996) used a cone -plate rheometer. Lastly, Wang and Gordani-nejad (2006), used a piston -driven flow-mode- type rheometer to measure the apparent viscosity and yield stress of MR fluids at high shear rates.

The flow loop which was designed and constructed for the experiments in our lab is shown schematically in Figure 1.

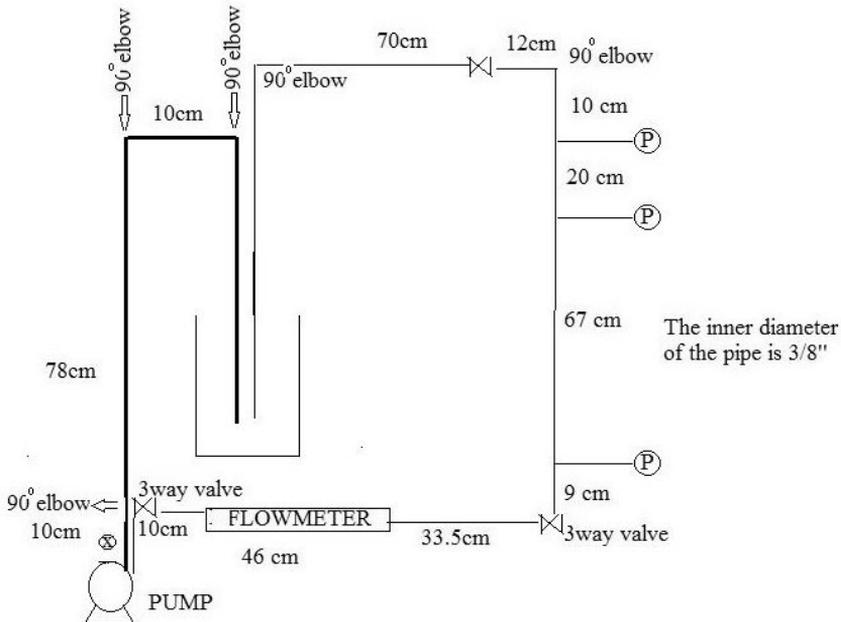
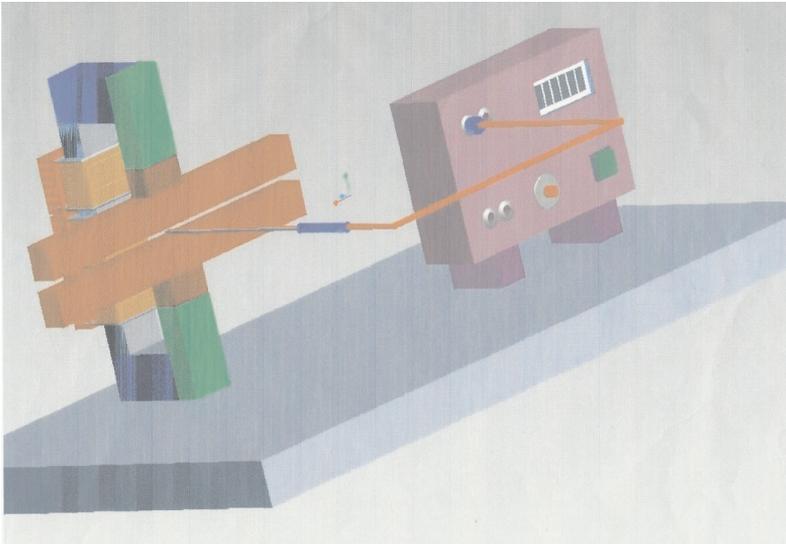


Fig. 1. Sketch of the Magnetorheometer setup

The parameters which are monitored using this setup are flow rate, density, temperature, pressure, pressure drop and magnetic flux. The system is consisted of vertical non- magnetic pipes with an inner diameter of 3/8". Flow is provided by a peristaltic hose pump, (Verdeflex VF15, maximum flow rate 400 l/h). In these type of pumps, the medium does not come in contact with any moving parts and is totally contained within a robust heavy duty hose. These pumps are suitable for viscous and high solid content fluids. The advantage of this pump in our application is that the iron particles will not cause corrosion. Disadvantage may be pulsation of the flow which can be overcome with the use of pulsation dampeners. Total volume of the flow system was purposely made small, at a value of 300 ml, so that there will be no need for using or making large volumes of expensive fluid.

The flow rate, the density and the temperature of the fluid are measured by a Coriolis flowmeter (Proline Promass 80I, Endress and Hauser) with a measuring range of 0–180000 kg/h. The measurement principle of this flowmeter is based on the generation of Coriolis forces, which are present when both translational and rotational movements are superimposed. The Coriolis force depends on the moving mass  $m$  the velocity  $u$  in the flow system and thus in the mass flow. The promass sensor uses oscillation. This has as a result the tube through which the fluid is flowing to oscillate. The Coriolis forces produced at the measuring tubes cause a phase shift in the tube oscillations.

The system is equipped with three pressure transducers (S-11, Wika). The transmitters feature a flush diaphragm process connection. Diaphragm transducers are designed for the measurement of viscous fluids or media that may contain high percentage of solids which may cause clog. The measurement range of the two transmitters which will be used for the measurement of the pressure loss over a distance of 67 cm is 0 to 16 bars and the range of the third pressure transducer which is designed to be used for the measurement of the absolute pressure, is 0–10 bar. Their accuracy is 0.25% full scale.



**Fig. 2.** Sketch of the electromagnet

The electromagnet used is constructed in the lab and it can provide flux densities up to 1 Tesla. A sketch of the electromagnet is shown in Figure 2. The magnetic flux is measured by a Gaussmeter (GM08, Hirst Magnetic Instruments Ltd). The measurement range of the gaussmeter is 0 to 3 Tesla while its reproducibility is 0.5%. The signals of all the sensors are collected and analyzed via a data acquisition system.

#### 4. ISSUES ON SETTING UP THE FLOW SYSTEM

The flow system is ready now. The main problem of it is the pulsation of the flow, due to the peristaltic pump. In order to reduce the pulsation to a minimum and ideally have a steady flow, a bladder type pulsation damper will be added to the system. It is expected that the pulsation will be reduced up to 90%.

The magnet is being built and once finished it will be put on the flow system so that measurements will start. These will involve using various MR fluids with different concentrations and we will be monitoring their behavior under different magnetic fluxes. Measurements will include pressure drop for series of flow rates and then, utilizing the model and methodology of Kelessidis *et al.* (2011), matching of experimental data with predictions will give the yield stress of the fluids as a function of magnetic flux.

#### 5. CONCLUSIONS

A new magneto-rheometer setup is presented. It is designed and built to determine the tunable rheological properties of MR fluids. All parts of the system are selected, so that the flocculation and the settling of the magnetic particles won't cause any damage to them or any problem to the measurements. By measuring the pressure drop at different flow rates and magnetic fields the rheological properties of the fluids will be evaluated. The rheometer will be tested by using a commercial MR fluid (MRF 122EG, LORD) and by fluids which will be made in our lab. The MR fluids with different components will be used in order to determine the most optimal composition for use in drilling applications.

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