

**A ROTATING CYLINDER VISCOMETER FOR MEASURING THE  
VISCOSITY OF MAGNETO-RHEOLOGICAL FLUIDS**

By

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## **ABSTRACT**

A rotating cylinder viscometer was designed and constructed for the purpose of measuring the viscosity of magneto-rheological fluids. The motivation underlying this thesis was the result of a strong interest in the unusual properties of magneto-rheological fluids which have potential use in a variety of applications, including shock absorbers, valves, clutches, brakes, robotic actuators and seals. The following work contains an introduction to magneto-rheological fluids, a theoretical background on viscosity, an explanation on how to build a rotating cylinder viscometer and data collected on the viscosity of air, water, a sample MR fluid, and a self made magnetic fluid sample.

## TABLE OF CONTENTS

Senior thesis acceptance	i
Abstract	ii
Table of Contents	iii
List of figures	iv
List of tables	v
<b>I. Introduction</b>	<b>1</b>
<b>II. Magneto-Rheological fluids</b>	<b>2</b>
<b>I. Ferro magnetic fluids</b>	<b>3</b>
<b>II. How to create magneto-rheological fluids</b>	<b>6</b>
Electro-Rheological fluids	<b>9</b>
<b>III. Viscosity</b>	<b>11</b>
A. Definition	<b>11</b>
B. Measurement of viscosity	<b>13</b>
<b>IV. Rotating cylinder viscometer</b>	<b>17</b>
<b>IV. Experimental</b>	<b>24</b>
The viscosity of air, water and glycerin	<b>24</b>
The viscosity of MR fluids	<b>26</b>
<b>IV. Results &amp; Conclusion</b>	<b>32</b>
Acknowledgments	<b>34</b>
References	<b>35</b>

## LIST OF FIGURES

		Page #
Fig. 1	The molecules and their dipole arms before and after subjected to a magnetic field.	3
Fig. 2	An iron rod in a dish of MR fluids shown before and after an introduced current and magnetic field.	6
Fig. 3	The shear viscosity between two plates.	12
Fig. 4	The polyamide rotor submerged in the MR fluid being held in the cup.	14
Fig. 5	An exaggerated drawing of the viscometer to illustrate the path of the magnetic field lines after an induced current.	18
Fig. 6	A scale drawing of the complete viscometer.	19
Fig. 7	An illustration of end effects.	20
Fig. 8	The dimensions of the top plate making up the “cup” or gap width, used to hold the MR fluids.	21
Fig. 9	A side view of the aluminum and polyamide rotor.	23
Fig. 10	A graph of viscosity vs. current for a constant $\omega$ with sample #1.	29
Fig. 11	A graph of viscosity vs. current for a constant $\omega$ with sample #2.	30
Fig. 12	A graph of viscosity vs. current for a constant $\omega$ with sample #3.	31

## LIST OF TABLES

		Page #
Table I	A list of solids and their respective ferromagnetic Curie temperatures.	5
Table II	A list of fluids and their respective viscosities at certain temperatures.	13
Table III	Wire diameters, their number of turns and maximum allowed current.	22
Table IV	Data taken on three sample MR fluids.	28

## I. INTRODUCTION

Magneto-rheological (MR) fluids have been the focus of increasing interest for over thirty years due to their magnetic field dependent viscosity. Under normal conditions MR fluids, composed of micron sized magnetic particles suspended in oil, behave as a free flowing liquid with properties similar to those of motor oil. However, when exposed to an external magnetic field, these fluids are spontaneously magnetized and are able to transform into near-solid states within milliseconds. Just as quickly, the fluid can return to its liquid state with the removal of the field. The degree of viscous change in a MR fluid is proportional to the magnitude of the applied magnetic field<sup>5</sup>.

The work reported here was motivated by the unusual properties and numerous applications, only limited by the imagination, that result from the use of a material with the properties of a liquid and the characteristics of a ferromagnetic material. MR fluids have potential application in resistance devices on exercise equipment, as suspension devices in vehicle seats, clutches, brakes, and dampers. MR fluids offer the potential for unprecedented control of vibration and motion in diverse industrial and consumer applications.

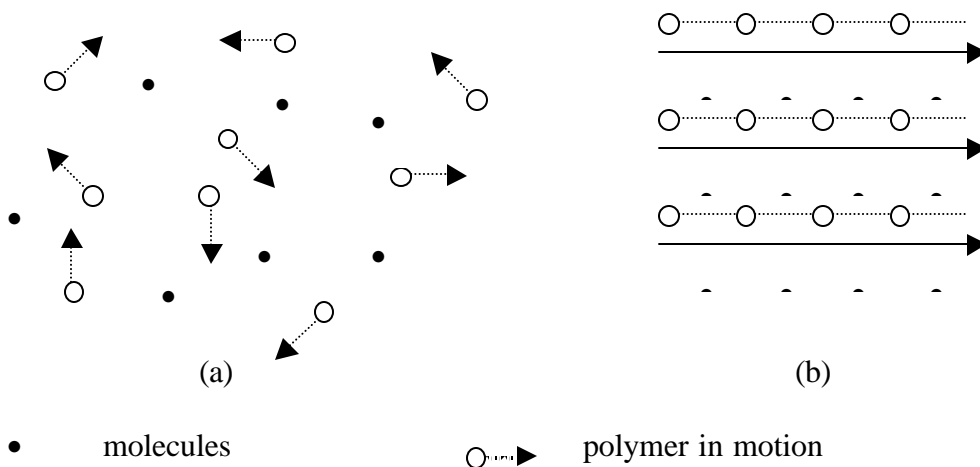
The magazine *The Economist* foresees that these fluids will have a tremendous economic impact in the industry of fast response mechanical devices<sup>11</sup>. However, no large scale industrial fabrication of these devices has been implemented because MR fluids are still being researched. There remains a need for reliable measurement methods and apparatus design that work under conditions close to practical situation (i.e. with high energy dissipation).

## II. MAGNETO-RHEOLOGICAL FLUIDS

Taking advantage of the unique properties of MR fluids has been a focus in research for over 30 years. Jacob Rabinow first utilized the properties of magnetic fluids in the late 1940's<sup>10</sup>. In December 1948 Rabinow published an article titled, "The Magnetic Fluid Clutch." This article released information that a new type of magnetic fluid had been discovered at the National Bureau of Standards. This fluid, composed of approximately 90 per cent carbonyl E iron and 10 per cent light machine oil, was found to have strange, yet useful properties.

Rabinow pointed out in his early work that putting a magnetic material (i.e. iron filings) on a liquid carrier will produce a magnetic fluid with unusual properties. When introduced to a magnetic field these liquids experience unusual phenomena. The iron particles become "mutually attracted, bind together in the field, and the mixture seemingly solidifies<sup>10</sup>." As early as the late 1940's this property proved extremely useful, and Rabinow recognized its potential use as a clutch fluid.

Prior to an induced magnetic field, MR fluids behave as a normal liquid and the individual dipole arms are arranged randomly (Fig. 1a). However, after the introduction of a magnetic field, the individual magnetic dipoles become aligned in the direction of the field (Fig. 1b). The strength of this alignment is directly related to the strength of the magnetic field.



Once the field is on and the dipoles align themselves, the liquid suddenly becomes “harder” and more viscous. However, after the field is turned off, the fluid spontaneously returns to a less viscous state.

### **A. Ferro magnetic fluids**

Although magnets and magnetic materials are used in thousands of household applications and even more in industry, the general population does not know much about how magnets work, let alone what magneto-rheological fluids are and how they work.

There are two types of magnets, electromagnets and permanent magnets. Electromagnets are created by coiling a current carrying wire around an iron core. The strength of the electromagnet is directly proportional to the current. The more familiar permanent magnet, however, does not need a current to have a magnetic field, rather the field is the combined effect of magnetic moments associated with electron spin.

When we speak of magnetism in everyday conversation, we are usually referring to the simplest, most practical uses. This includes images of permanent magnets picking up tools or of magnetic pieces used to show off a report card on the refrigerator. This type of magnetism familiar in our daily experience is called ferromagnetism.

Of the elements, only iron (Fe), cobalt (Co), nickel (Ni), gadolinium (Gd), and dysprosium (Dy) are ferromagnetic, although there are a large number of ferromagnetic alloys and oxides (Table I). These elements, alloys and oxides form special interactions, called exchange couplings, in which the electron spin dipoles are aligned.

Ferromagnetism is temperature dependent. If the temperature of a ferromagnetic fluid is raised above a certain value, known as the ferromagnetic Curie temperature,  $\theta_f$ , the exchange coupling decreases and the spontaneous magnetization vanishes. At this point most materials become paramagnetic, a weaker form of ferromagnetism<sup>5</sup>.

Table I. A list of solids and their respective ferro-magnetic Curie temperatures.

Solid	Curie temperature, $\theta_f$ (°K)
Fe	1043
Co	1400
Ni	631
Gd	289
Dy	105
MnBi	630
Cu <sub>2</sub> MnAl	603
Cu <sub>2</sub> MnIn	506
MnAs	318
MnB	533
Mn <sub>4</sub> N	745
MnSb	587
MgOFe <sub>2</sub> O <sub>3</sub>	583

Simply stated, ferro-magnetic fluids are those fluids with the properties of ferromagnetism. Similar to a solid ferro-magnet's ability (i.e. a compass needle) to move or change orientation with an external field (i.e. earth's magnetic field), MR fluids, when acted upon by an external field are able to change their properties. A magnetic field on a MR fluid acts almost independently on every microscopic volume of the liquid, yielding a complex response.

Figure 2 illustrates the strange properties of MR fluids. In Fig. 2a, an iron rod is submerged in the center of a shallow pool of MR fluids. A current in the rod immediately causes the fluid to become magnetized drawn upward along the rod, forming a symmetrical concave meniscus around the iron rod (Fig. 2b).

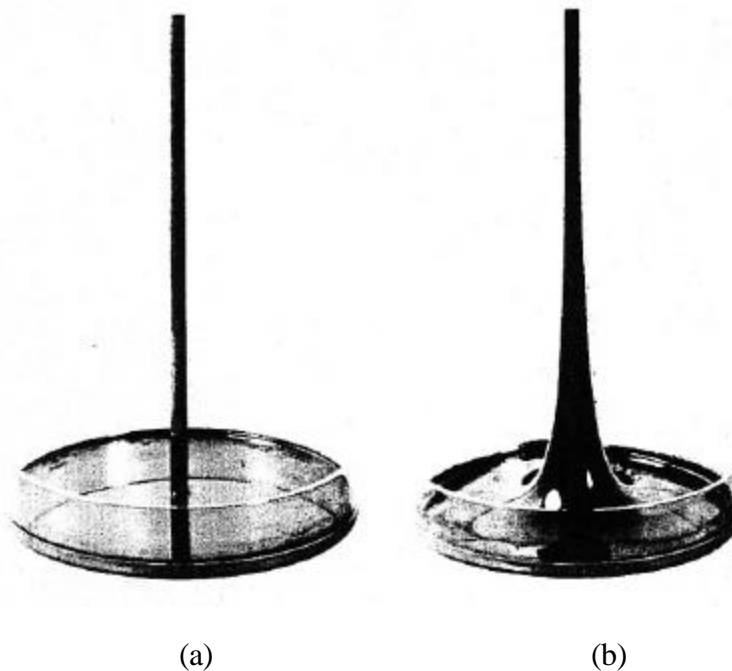


Fig 2. An iron rod in a dish of MR fluids. The fluid acts as a normal liquid when no current is passed through the rod (a), however, after a current is introduced the liquids spontaneously “jump” up the rod (b).

## B. How to create MR fluids

MR fluids are not found in nature, they must be created. The only way to find advanced MR fluids is high tech labs. A sample MR fluid was received from Advanced Fluid Systems, in London, courtesy of Mark Hinrichs. However, the exact make up of the fluid was not disclosed.

After contacting AFS in regards to the type of sample I had received, a representative quickly responded:

*“It was used in some general functional testing on some dampers that we put together. The formulation is something that our supplier will not discuss with us, for the simple reason that they do not want us to go into competition with them.”*

This response illustrates the value of MR fluids, the complexity of creating a MR fluid, and the rising competitive market for such fluids.

Although AFS’s suppliers would not release their recipe, an explanation can be unraveled by simply knowing something about ferromagnetism. Ferromagnetism, as explained in section IIA, is a property of iron, nickel, cobalt and some compounds and alloys of these elements. When a ferromagnet is subjected to a magnetic field the magnetic dipoles (Fig. 1) line up in a north-south orientation and create a magnet. It may seem that by simply heating iron, nickel, or cobalt until they become molten would yield a magnetic fluid. However, this is impossible because the characteristic exchange

coupling disappears above the Curie point (discussed in Sec. IIA), which is far below the melting point of metals.

Although the characteristics of ferromagnetism are hard to achieve as a liquid, it is possible nonetheless to create a stable magnetic fluid. The basic idea behind creating magnetic fluids is to form a colloid in which very small ferromagnetic particles are suspended in a liquid carrier.

One of the first colloidal systems was developed by Stephen Papell of the National Aeronautics and Space Administration in the early 1960's. Papell's creation consisted of finely divided particles of magnetite (a molecular mixture of the iron oxides  $\text{FeO}$  and  $\text{Fe}_2\text{O}_3$ ) suspended in kerosene. Papell added acid (serving as a surfactant or dispersing agent) in an effort to keep the particles from clumping together. Although magnetic particles had been in magnetic clutches since the 1940's, Papell's formula was unique because the particles in Papell's ferrofluid were 1,000 times smaller in linear dimensions (over a billion times smaller in volume). Papell showed that a magnetic clutch fluid is very effective under the influence of a magnetic field due to its smaller size. When magnetically active the fluid is very viscous, yet remains a liquid. Papell's work with ferrofluids influenced the scientific community to seriously consider the application of magnetic fluids<sup>2</sup>.

### **C. Electro-Rheological fluids**

Electro-rheological (ER) fluids are a type of fluid whose properties can be altered under an electric field. ER fluids, with their ability to change characteristic under an electric field, also have much potential in a number of applications.

After subjected to an electric field ER fluids are able to turn from liquid to solid and vice versa. Solids and liquids differ only in the arrangement of their atoms. The atoms in a solid are relatively stationary in ordered rows and the atoms in a liquid are moving much faster in random directions (Fig. 1). If cooled enough, any liquid can turn itself into a solid. However, it may take a while before enough heat is removed and the random, fast moving molecules settle. Due to the internal make up of ER fluids, they are able to change instantaneously from a liquid to a solid without removing any heat.

ER fluids are created by adding certain polymers to a liquid carrier. Similar to the molecules in “normal” (i.e. Newtonian) liquids, each polymer molecule ignores its neighbor and moves around conforming to the shape of its container. However, when subjected in an electric field, the polymers form long strings and instantly becomes a solids. This is similar to the alignment of magnetic dipoles of an MR fluid after the introduction of a magnetic field. The extremely strong solid that results takes over 2,000 Volts per millimeter to create. The same electric field used to light up a television screen can be used to turn a liquid into a solid.

The strength of the ER solid increases as the electric field increases, similar to how the viscosity of a MR fluid increases proportionally with an increased field. Then, once the field is released, the ER solid spontaneously turns back into a liquid.

There are many applications for a liquid that is able to spontaneously turn from liquid to a solid. For instance, hydraulic fluids are used to push pistons out of a cylinder. However, in order to control the movement of a piston a valve has to control the flow of the fluid. Until the discovery of ER fluids magnetic relays were the only method of

closing and opening the valves. Now, ER fluids can be used to close a rheological valve by simply putting an electric field across it. To open a valve, the electricity is simply switched off. The use of ER fluids in hydraulic fluids may reduce wear, save space, and cut the cost of the valve's seal (which would no longer need to fit tightly because the ER fluid could take up any required shape before turning itself into a solid seal). ER fluids could easily be found useful in hydraulic systems, which rang from aircraft landing-gear to factory robots<sup>11</sup>.

Under an applied field MR fluids are 20-50 times stronger than ER fluids. MR fluids can also be operated directly from low-voltage power supplies and are far less sensitive to contaminants and extremes in temperature. Applied to a variety of devices, MR fluid technology can provide flexible control capabilities in designs that are far less complicated and more reliable than ER fluid products.

### **III. VISCOSITY**

#### **A. Definition**

Viscosity is the property of a material that measures a fluid's ability to resist flow. Historically, viscosity was a measurement of a gas, however, today it is used synonymously with liquids. A simple comparison of two viscous fluids can be illustrated by imagining honey and water flowing from a jar. Although the force of gravity is the same in both cases, the more viscous fluid (in this case, honey) flows more slowly. The standard SI units of viscosity are the pascal-seconds, shown in Eq. (1) derived from the less conventionally used unit, the poise.

$$\begin{aligned}
 1 \text{ poise} &= 1 \text{ g}/(\text{cm}\cdot\text{sec}) & (1) \\
 &= .1 \text{ kg}/(\text{m}\cdot\text{sec}) \\
 &= .1 \text{ Pa}\cdot\text{sec}
 \end{aligned}$$

The shear viscosity can be measured in an experiment in which the fluid of interest is sheared between two flat plates parallel to one another (Fig. 3). Known as planar Couette flow, the shear stress is given as the ratio of the tangential force,  $F$ , needed to maintain the moving plate at a constant velocity,  $V$ , to the plate area,  $A$ . The velocity,  $V_x$ , parallel to the plates at a perpendicular distance,  $y$ , above the stationary plate, the shear flow created between the plates is given by

$$u_x = \frac{F}{\eta} y \quad (2)$$

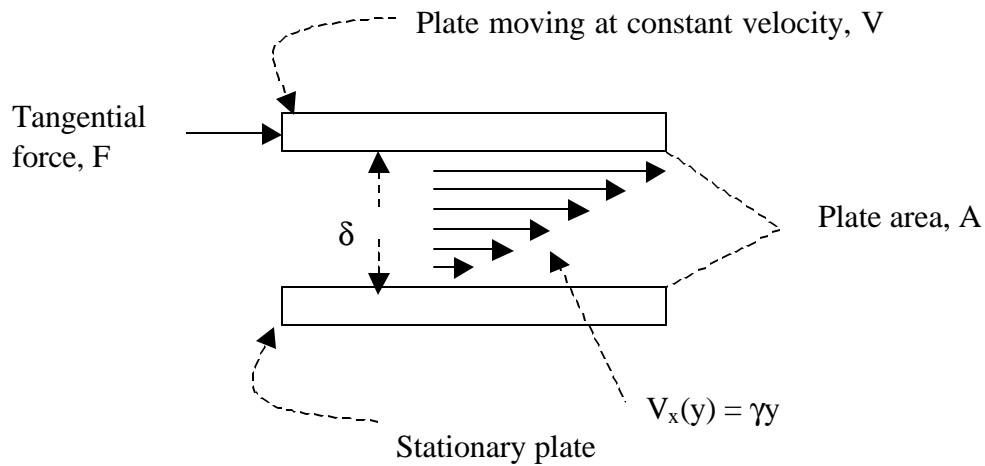


Fig 3. The shear viscosity between a moving and stationary plate.  $\eta$  by  $V/d$  where  $d$  is the distance between the plates. These quantities only depend on the liquid between the plates.

The shear viscosity,  $\eta$ , is defined as

$$\mathbf{h} \equiv \frac{\text{shear stress}}{\text{shear rate}} = \frac{F/A}{V/d} \quad (3)$$

For comparison, the viscosity of several gases and liquids are presented in Table II<sup>9</sup>.

Table II. A list of fluids and their respective viscosities at certain temperatures.

Fluid	Temperature		Viscosity, $\eta$
	°C (°F)		centipoise
Air (gas)	-104	(-155)	.01130
	0	(32)	.01708
	74	(165)	.02102
Hydrogen (gas)	0	(32)	.00835
Ethane (gas)	0	(32)	.00848
Water (liquid)	5	(41)	1.519
	20	(68)	1.002
	95	(203)	.2975
Mercury (liquid)	0	(32)	1.685
Ethyl alcohol (liquid)	0	(32)	1.773
Olive oil (liquid)	10	(50)	138.0
Glycerin	0	(32)	12,110.0

## B. Measurement of viscosity

In 1687, Isaac Newton suggested a model to describe the viscous property of fluids. He proposed that the resistance to flow of a fluid is proportional to the velocity at which the parts of the fluid are being separated from each other. Although Newton's law

of viscosity is an idealization, many fluids, such as low molecular weight liquids, adhere to these laws over a large range of conditions.

Many other fluids, however, are not described well by Newton's laws. These non-Newtonian fluids include polymer solutions, blood, and ink. In general MR fluids would be classified as non-Newtonian liquids.

A rotational cylinder viscometer, shown in Fig. 6, was selected as the instrument with which to measure viscosity of the sample MR fluid. Dimensions used in calculating the viscosity are shown in Fig. 4 for a small, yet important section of the viscometer.

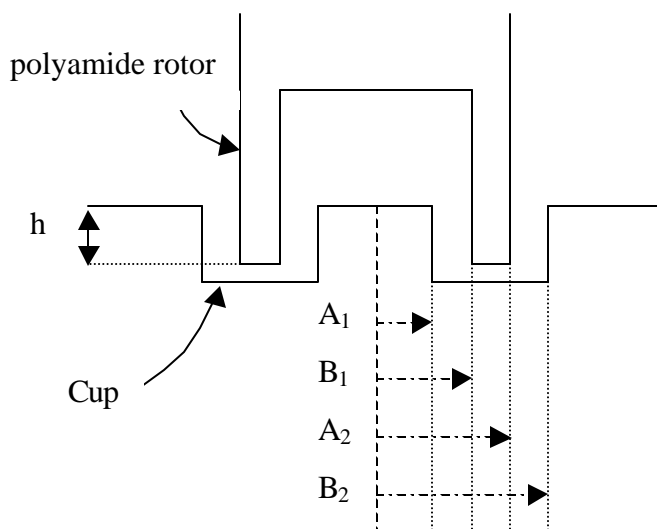


Fig 4. The polyamide rotor submerged in the MR fluid, which is held in the cup.

If a liquid is held in a cup, and a polyamide rotor, is immersed in the liquid and rotated at a constant speed around its central axis, the rotor will experience a retarding force due to the viscous drag of the liquid. By knowing the dimensions shown in Fig. 4 the viscosity of the liquid,  $\eta$ , can be calculated.

The torque,  $\tau$ , on the rotor, rotating with angular velocity  $\omega$  is given by<sup>7</sup>

$$t = 4\mathbf{p}h \left( \frac{A_1^2 B_1^2}{B_1^2 - A_1^2} + \frac{A_2^2 B_2^2}{B_2^2 - A_2^2} \right) \mathbf{w}. \quad (4)$$

with,

$$\mathbf{w} = 2\mathbf{p}/t$$

$t$  = the time of one revolution in seconds.

Knowing that

$$P = \mathbf{t}\mathbf{w} = iv \quad (5)$$

with

$i$  = the current powering the motor

$v$  = the voltage of the motor,

we can solve for the power

$$P = 4\mathbf{p}h \left( \frac{A_1^2 B_1^2}{B_1^2 - A_1^2} + \frac{A_2^2 B_2^2}{B_2^2 - A_2^2} \right) \mathbf{w}^2. \quad (6)$$

Rearranging Eq. (6) yields a measurement, in Pa-sec, of

$$\mathbf{h} = \frac{P}{4\mathbf{p}h\mathbf{w}^2} \left( \frac{A_1^2 B_1^2}{B_1^2 - A_1^2} + \frac{A_2^2 B_2^2}{B_2^2 - A_2^2} \right)^{-1}, \quad (7)$$

or

$$\mathbf{h} = k \left( \frac{P}{\mathbf{w}^2} \right) = k \left( \frac{iv}{\mathbf{w}^2} \right), \quad (8)$$

with the constant

$$k = \frac{1}{4h\boldsymbol{\rho}} \left( \frac{A_1^2 B_1^2}{B_1^2 - A_1^2} + \frac{A_2^2 B_2^2}{B_2^2 - A_2^2} \right)^{-1} \frac{1}{m^3}. \quad (9)$$

The dimensions of Fig. 4 have the following values,

$$\begin{aligned} A_1 &= .01525\text{m} \\ A_2 &= .01184375\text{m} \\ B_1 &= .0169375\text{m} \\ B_2 &= .020125\text{m} \\ h &= .006\text{m} \end{aligned}$$

Using these, Eq. (9) yields

$$k = 9191 \text{ m}^{-3}.$$

Then, knowing the current and voltage used to power the rotor and the angular velocity,  $\omega$  (kept constant), the viscosity can be determined from Eq. (8). As shown, the power required to maintain a constant  $\omega$  increases linearly with respect to viscosity.

#### **IV. A ROTATING CYLINDER VISCOMETER**

The dependence of viscosity on the magnetic field intensity is one of the important characteristics of a MR fluid. In an effort to measure the magnetic field dependence of MR fluids, a rotating cylinder viscometer was designed and constructed, using the design of Martin H. Laun as a guide<sup>8</sup>.

The theory underlying the construction of a rotating cylinder viscometer is fairly simple. However, an important preliminary step is understanding how an applied magnetic field effects the viscosity of MR fluids. With this consideration, the design and

location of the cup used to hold the MR fluids is crucial in an effort to maximize the field dependence of MR fluids on viscosity. Ideally, the cup is located so that the magnetic field lines pass through the liquid perpendicular to the rotor. By doing this the individual dipoles of the ferromagnetic particles in the liquid carrier will align themselves spontaneously in the magnetic field, as shown in Fig. 1.

The electro-magnet was constructed using these two parts. Using an iron rod, a solenoid was put inside the pipe and closed off with two iron plates. A complete, relatively accurate scale drawing is shown in Fig. 6.

Figure 5 illustrates the direction the magnetic field lines take as they approach the cup. The direction of these lines is crucial in measuring the MR fluid dependence on viscosity. If these lines are not parallel to the cup and perpendicular to the rotor the viscosity measurement will be affected.

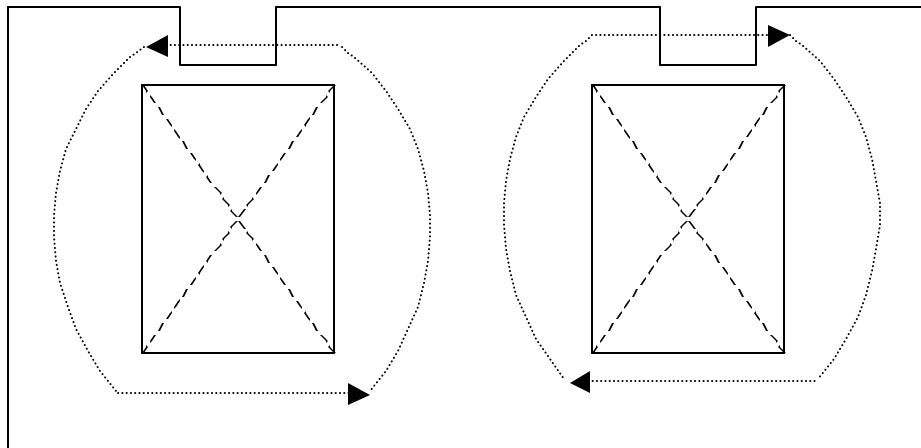
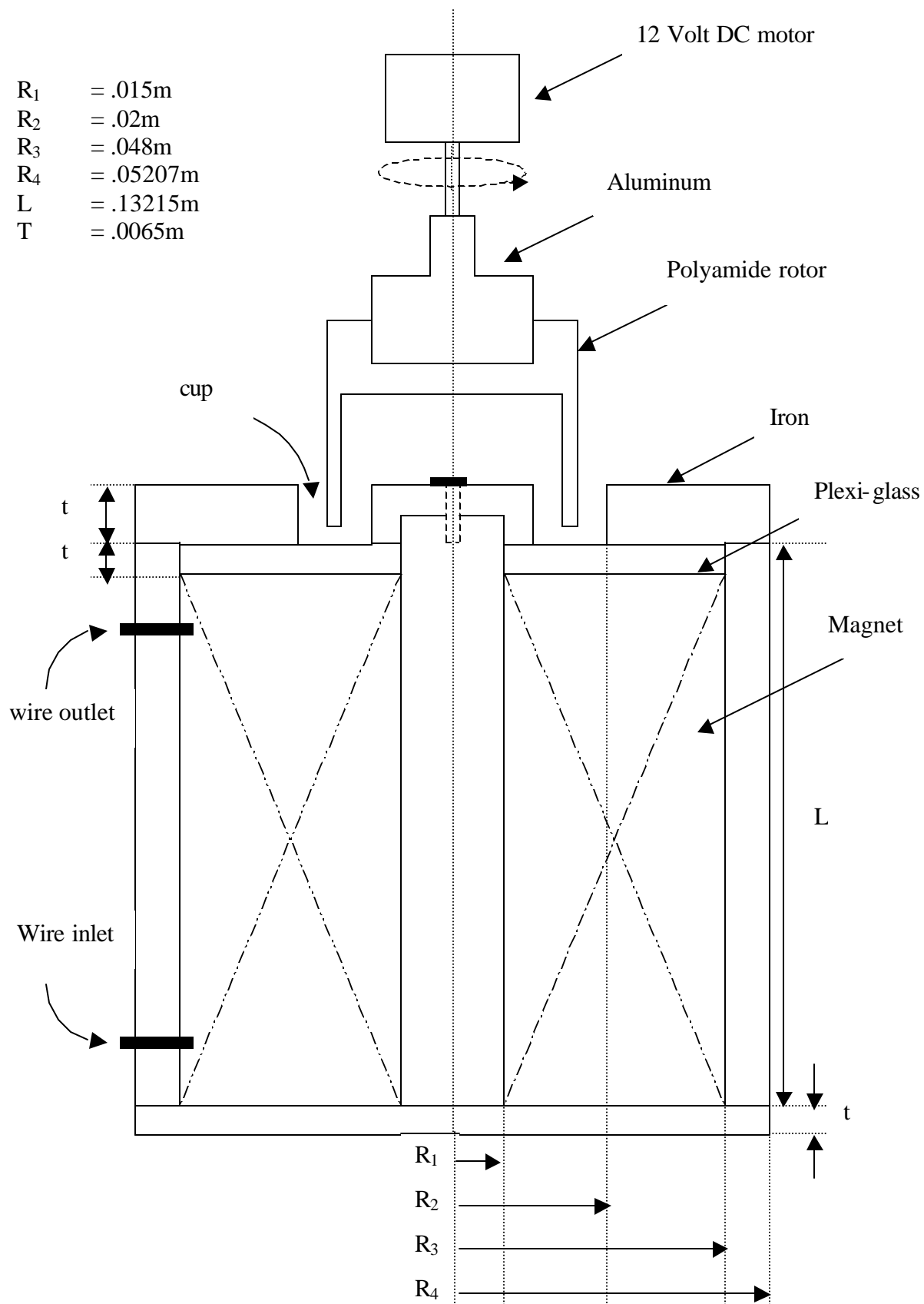


Fig 5. An exaggerated drawing of the viscometer to illustrate the path of the magnetic field lines after an induced current.



Most of the field lines run perpendicular, however, a few cross the cup in-between the floor of the cup and the bottom of the rotor. Illustrated in Fig. 7, these lines run parallel to the rotor and produce end effects altering the measurement of viscosity. Minimizing  $d$  decreases the severity of end effects.

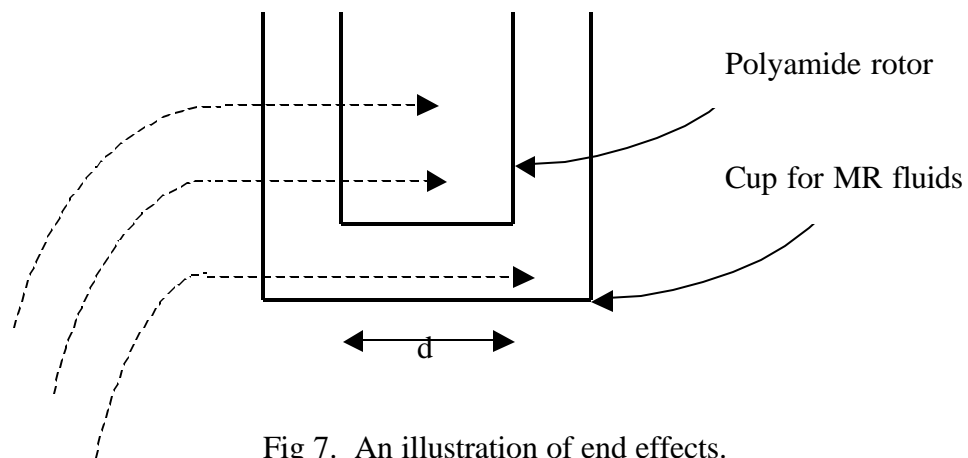


Figure 8 shows the design of the cup. In order to ensure the field lines pass through the cup perpendicular to the rotor, a plexi glass piece was used as the floor of the cup.

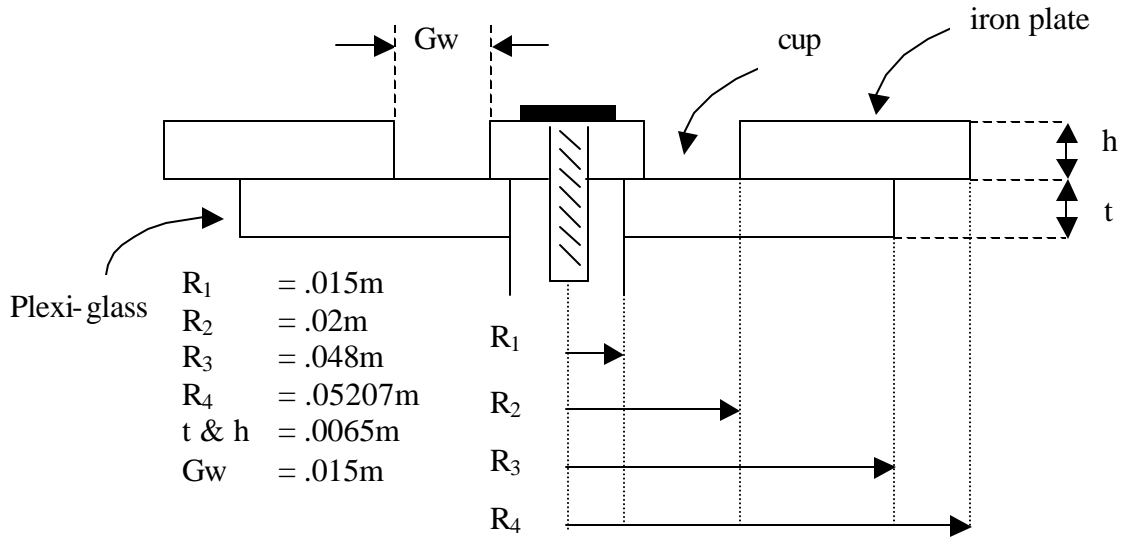


Fig 8. The dimensions of the top plate making up the “cup” or gap width, used to hold the MR fluids.

The dimensions of the inner and outer radius were determined by estimating a magnetic field of .4 T using 10 amperes of current. The strength of the magnetic field at the center of the rod, given in Eq. (10), provided means to determine  $R_1$  and  $R_2$ .

$$B = .5 \mu_0 I L \times L n \left( \frac{a + (a^2 + b^2)^{1/2}}{1 + (1 + b^2)^{1/2}} \right) \quad (10)$$

with,

$$n = N/A = \text{number of turns / area} \quad \mu = \text{constant}$$

$$I = \text{current in amperes} \quad \beta = L / 2R_1$$

$$L = \text{Length of the rod} \quad \alpha = R_4 / R_1$$

With this information, Table III was compiled and the appropriate wire diameter was selected.

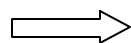
Table III. Wire diameter, their number of turns and maximum allowed current.

Gauge #	Diameter (m)	$n=1/D^2$ (m)	amperes
10	0.00258	149,274.01	25-35
12	0.00205	237,415.90	20-30
14	0.00163	377,238.90	15-20
16	0.00129	600,627.40	6 to 10
18	0.001016	968,751.90	3 to 6

It was discovered that the desired results could be obtained by using a standard annealed copper wire of diameter .00163m (14 gauge) and a length, L, of .12805m. Through trial and error the inner radius,  $R_1$ , and outer radius,  $R_4$ , were calculated to be .01125m and .04318m, respectfully.

$$M = L \times Ln \left( \frac{(R_4 / R_1) + [(R_4 / R_1)^2 + (l/2R_1)^2]}{1 + [1 + (l/2R_1)^2]^{1/2}} \right) \quad (11)$$

L= .12805 m  
 R1= .01125 m  
 R4= .04318 m  
 I= 10 amperes  
 B= 0.4 T



M= .172  
 d= 0.001647 m

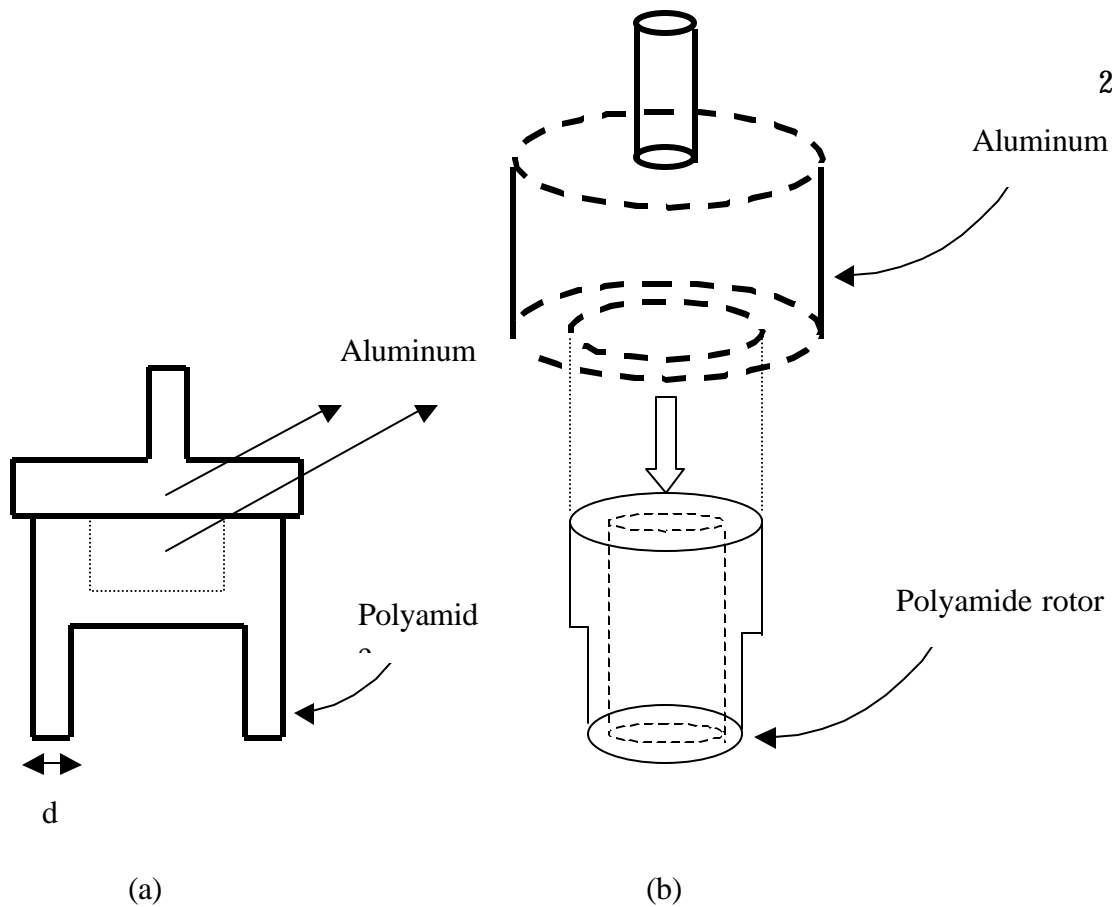


Fig 9. Side view of the aluminum and polyamide rotor (a); and a three dimensional view of how the two pieces fit together (b).

## V. EXPERIMENTAL

In an effort to test the sensitivity of the viscometer, a comparison of the viscosity of air, water, glycerin was made. Knowing the standard values of the viscosity of air, water, and glycerin gave a reference point for which an assessment of the precision of the viscometer could be made. The viscosity of the three different sample MR fluids was tested after measuring the viscometer's accuracy. These viscosities were calculated using Eq. (8). The angular velocity,  $\omega$ , was determined using a photo gate, and the power used by the motor was measured using a multimeter.

### A. Viscosity of air, water, and glycerin

Operating the rotor in air, the photo gate measured the angular velocity of the rotor knowing the time,  $t$ , it took for one revolution. Then, A measurement of viscosity was made knowing the constant,  $k$ , and the power,  $P$ , used by the motor.

$$\mathbf{h}_{\text{measured}} = \frac{kP}{\mathbf{w}_{\text{air}}^2} = .721 \text{ pa - sec} \quad (8)$$

with,

$$\begin{aligned} P &= iv = (.001A)(13V) = .013W \\ \mathbf{w} &= 2\mathbf{p}/t = 2\mathbf{p}/.4880\text{sec} = 12.87\text{Rad / sec} \\ k &= 9191\text{m}^{-3}. \end{aligned} \quad (12)$$

The accepted measured value of the viscosity in air at 20° C is

$$\mathbf{h}_{\text{accepted}} = \frac{kP}{\mathbf{w}_{\text{air}}^2} = 1.84 \times 10^{-5} \text{ Pa - sec.} \quad (13)$$

Although this gave a large error in the measurement, the rotating cylinder viscometer was not expected to have the sensitivity to accurately measure the viscosity of air. Next, a measurement of the viscosity of water was made. When performing this measurement, it was important to recognize that not all the power is absorbed as friction by the rotor. In fact, much of the power is absorbed inside the motor (i.e. in the gears). So, when calculating the power of the motor, Eq. (14) was used, with each value ran at the same angular velocity.

$$\text{Power absorbed} = P_{\text{in the fluid}} - P_{\text{in the air}} \quad (14)$$

Then, using Eq. (8)

$$\mathbf{h}_{\text{measured}} = k \frac{(P_{\text{in water}} - P_{\text{in air}})}{\mathbf{w}_{\text{water}}^2} = k \frac{(.013W - .013W)}{\mathbf{w}_{\text{water}}^2} = 0 \quad (15)$$

with,

$$\begin{aligned}
 P_{\text{in water}} &= iv = (.00241A)(11.313V) = .013W \\
 P_{\text{in air}} &= iv = (.001A)(13V) = .013W \\
 \mathbf{w} &= 2\mathbf{p}/t = 2\mathbf{p}/.4879\text{sec} = 12.878\text{Rad /sec} \\
 k &= 9191m^{-3}.
 \end{aligned}
 \tag{12}$$

This is an indication, again, that the sensitivity is got great enough to calculate the viscosity of water. The accepted measured value of the viscosity of water at 20° C is

$$\mathbf{h}_{\text{accepted}} = 1.0 \times 10^{-3} \text{ pa - sec.}
 \tag{16}$$

Using the same techniques, a measurement of the viscosity of glycerin was made.

With Eq. (15)

$$\mathbf{h}_{\text{measured}} = k \frac{(P_{\text{in water}} - P_{\text{in air}})}{\mathbf{w}_{\text{water}}^2} = .602 \text{ Pa - sec}
 \tag{15}$$

with,

$$\begin{aligned}
 P_{\text{in glycerin}} &= iv = (.00324A)(11.96V) = .0387W \\
 P_{\text{in air}} &= iv = (.00246A)(11.352V) = .0279W \\
 \mathbf{w} &= 2\mathbf{p}/t = 2\mathbf{p}/.4880\text{sec} = 12.875\text{Rad /sec} \\
 k &= 9191m^{-3}.
 \end{aligned}$$

At room temperature (approximately 20°C), the accepted viscosity of glycerin is given in Eq. (17).

$$\mathbf{h}_{\text{accepted}} = 1.5 \text{ Pa - sec}^9.
 \tag{17}$$

The measurements of viscosity of air and water yielded enormous errors due to the fact that the viscometer did not have the required sensitivity. However, a

measurement of the viscosity of glycerin yielded an error of much lesser degree, indicating the viscometer works.

### **B. Viscosity of sample MR fluids**

Next, using the same methods described above, a calculation of viscosity for three sample MR fluids was made. After the donated sample from AFS was tested in the viscometer disappointment struck as the fluid instantaneously froze and stalled the motor with even the smallest magnetic field. After the voltage supplying the motor was increased to 24 volts and the current creating the magnetic field decreased to 1mA the rotor still stood still. The sample MR fluids were too strong for the viscometer. In an effort to make a less viscous MR fluid, the sample MR fluid was diluted with 10W-30 motor oil and iron filings.

Table V shows data taken on the three samples. Sample #1 was composed of approximately 90 percent motor oil and 10 percent MR fluid; sample #2 was composed of 80 percent motor oil, 15 percent MR fluid, and 5 percent iron filings; and sample #3 was composed of approximately 95 percent motor oil and 5 percent MR fluid.

Keeping  $\omega$  constant was crucial in the testing the viscosity. Starting out with a relatively small motor voltage allowed an initial measurement of the rotor's angular velocity. After recording the power used by the motor and the angular velocity of the rotor, a measurement of viscosity was made. Next, after increasing the current to the magnet, it was necessary to increase the motor voltage to keep  $\omega$  constant. Adjusting the current accurately provides a new, higher, measurement of viscosity. Thus, each value for viscosity will correspond to a current value.

Table IV. Data taken on a three different sample MR fluid:  $\omega$ , the angular velocity;  $i$ , the current through the motor;  $v$ , the voltage supplying the motor;  $P$ , the power of the motor;  $I$ , the current creating the magnetic field; and  $\eta$ , the resulting viscosity.

$\omega$ (rad/s)	$i$ (amps)	$v$ (volts)	$P$ (watts)	$I$ (amps)	$\eta$ (Pa-sec)
<i>SAMPLE #1</i> $P_{in\ air}$ at $\omega = 5.7381$ Rad/sec is $(.001A)(6.6V) = .0066W$					
5.7381	.002	7	.014	.01	56.72
5.7381	.004	10	.04	.26	256.02
5.7381	.006	12	.072	.62	501.32
<i>SAMPLE #2</i> $P_{in\ air}$ at $\omega = 9.2277$ Rad/sec is $(.001A)(4.7V) = .0047W$					
9.2277	.002	10	.02	.01	303.3
9.2277	.003	11.1	.0333	.05	566.96
9.2277	.004	13	.052	.135	937.7
9.2277	.007	15.5	.1085	.25	2057.7
9.2277	.009	17.5	.1575	.44	3029.1
<i>SAMPLE #3</i> $P_{in\ air}$ at $\omega = 6.4238$ Rad/sec is $(.001A)(6.1V) = .0061W$					
6.4238	.002	8	.016	.01	95.11
6.4238	.003	9	.027	.115	200.8
6.4238	.004	11	.044	.22	364.1
6.4238	.0065	13	.0845	.42	753.2

Figures 11, 12 and 13 are graphs of relative viscosity vs. current for samples #1, #2, and #3, respectfully.

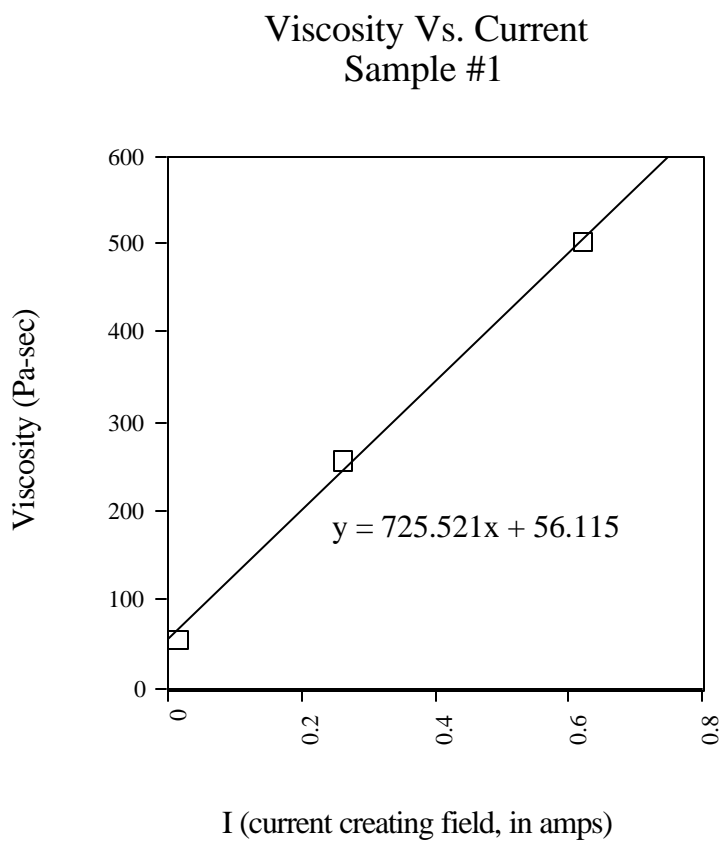


Fig 10. A graph of relative viscosity vs. current for sample #1 with a constant  $\omega = 5.7381$  rad/s.

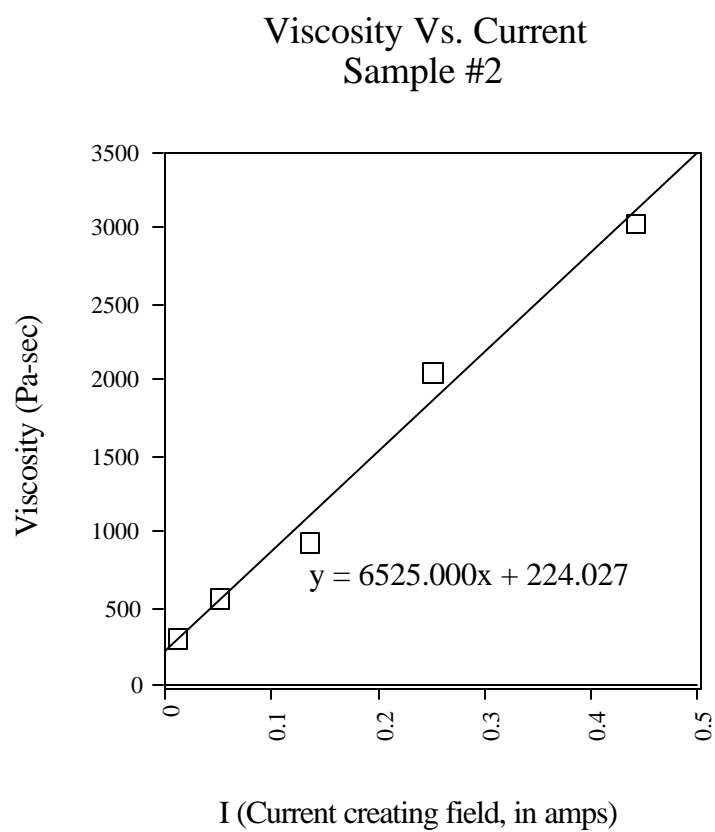


Fig 11. A graph of relative viscosity vs. current for sample #2 with a constant  $\omega = 9.2277$  rad/s.

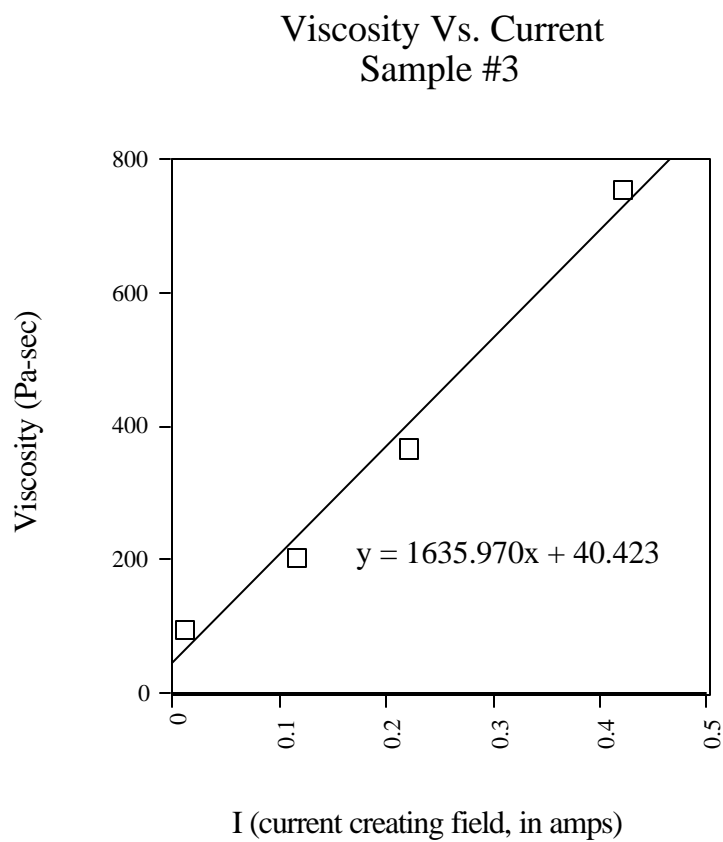


Fig 12. A graph of relative viscosity vs. current for sample #3 with a constant  $\omega = 6.4238$  rad/s.

## VI. RESULTS & CONCLUSION

The measurements of the viscosity of air, water and glycerin yielded high errors compared to accepted values, however, the increase in viscosity from air to water to glycerin provided information that the rotating cylinder viscometer was indeed working. The three graphs of viscosity versus current show that for different values of  $\omega$ , and for different mixtures of MR fluids, viscosity increases linearly as a function of current. This gives a good indication that the viscometer operates properly.

Sources of error include error in the motor (power is dissipated inside the motor), end effects (Sec. IV, Fig. 8), and lack of sensitivity of the viscometer. As discussed in Sec. IV, Fig. 7, the path the field lines take through the cup (ideally, parallel to the floor of the cup) is crucial in the strength of the field and in the measurement of viscosity. After placing iron filings around the cup and turning on the field, the filings immediately lined up entering the cup at undesired angles. If the lines do not enter and leave the cup parallel to the floor and perpendicularly to the rotor, then the stress on the rotor due to the viscous magnetic fluids will be less than calculated. End effects accounted for much error.

MR fluids have potential use in resistance devices on exercise equipment, as suspension devices on vehicle seats, in clutches, brakes, and dampers offering the potential for unprecedented control of vibration and motion in diverse industrial and consumer applications. Although MR fluids are still being researched, the ability to modify a fluid property could change virtually every aspect of hydrodynamics and

contribute to one of the many factors that will, inevitably, change the way we live our lives.

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