PROBLEM

How does the viscosity behavior of Ferro-fluids change when subjected to an external magnetic field under varied temperatures?

ABSTRACT

Suspensions of magnetic nano-particles (Ferro-fluids) exhibit normal liquid behavior coupled with magnetic properties. This leads to the possibility to control the properties and the flow of these liquids with external magnetic fields. The magnetic control enables the design of various applications as well as basic experiments in hydrodynamics. Ferro-fluids and their general properties are introduced and as an example, the control of its viscous property by applying external magnetic field is discussed. This property of Ferro-fluid is further expanded by varying the temperature of Ferro-fluids.

ALIGNMENT WITH THE NATIONAL AND STATE STANDARDS

Inquiry, Process and Problem Solving; uses science process skills in laboratory or field investigations, including observation, classification, communication, metric measurement, and prediction, inference, collecting and analyzing data.

SCSh2 Students will use standard safety practices for all classroom laboratory and field investigations.
SCSh3 Students will identify and investigate problems scientifically
SCSh4 Students will use tools and instruments for observing, measuring, and manipulating scientific equipment and materials.
SCSh5 Students will demonstrate the computation and estimation skills necessary for analyzing data and developing reasonable scientific explanations.
SCSh8 Students will understand important features of the process of scientific inquiry. Students will apply the following to inquiry learning practices; scientific
investigators control the conditions of their experiments in order to produce valuable data

GRADE LEVEL

Regular Physics and Honors Physics

SCHEDULE

Three days of regular 60 minutes Lab periods.

EXPECTED LEARNING OUTCOME

1. Students will get a deeper understanding of previously learned concepts (such as velocity, free-fall acceleration, temperature).
2. Students will understand the significance and strategy for connecting concepts and theories from different science topics (such as temperature, viscosity of fluids, magnetism, and free fall acceleration).

INTRODUCTION

What are Ferro-fluids? Ferro fluids are a stable suspension of nanometer sized solid magnetic particles in a carrier fluid. The particles are coated with a surfactant; a chemical which prevents the particles from clumping together and forming a solid mass. The most common type of Ferro fluid, presented here, is an oil based fluid consisting of magnetite particles. Ferro-fluid responds to an external magnetic field exhibiting the captivating property of “spikes” along the magnetic field lines, when placed in the proximity of a strong magnet.

An example of a spike patterns on a Ferro fluid surface. This image is adopted from Minako Takeno's web site about the Appearance of Magnetism.
APPLICATION

Ferro-fluids can be held in place simply via permanent magnets. This, in turn, enables their use as low-friction liquid seals against pressure differences (in turbo-pumps, for instance). They also act as highly efficient liquid bearings.

Ferro fluids are used in loudspeakers to enable enhanced thermal contact (for cooling) and better damping for the voice coils. Over 50 million loudspeakers sold in the US each year use Ferro fluids in this context.

Ferro fluids with larger particles (greater than 100 nm) change their viscosity significantly under applied magnetic fields. This happens because the particles align with the applied field and form chains across the width of the fluid container. This phenomenon is utilized in magnetic inertial dampers and active shock absorbers.

Pictures adopted from Liquids Research and Advanced Fluid Systems (acquired by Ferro Tec).

Keeping the focus on the viscous property of Ferro fluids, this experiment is designed.
KEY CONCEPTS

Briefly review the following scientific terms that students are already familiar with:

TEACHERS’ DOMAIN

Magnetism:

- Magnetism is a force that acts at a distance due to a magnetic field. This field consists of imaginary lines of flux caused by moving electrically charged particles or is inherent in magnetic objects such as a magnet.
- A magnet is an object that exhibits a strong magnetic field and will attract materials like iron to it.
- Magnets have two poles, called the north (N) and south (S) poles. Two magnets will be attracted by their opposite poles, and each will repel the like pole of the other magnet.
Permanent magnets are those once magnetized, they retain a level of magnetism. Temporary magnets are those which act like a permanent magnet when they are within a strong magnetic field, but lose their magnetism when the magnetic field disappears.

3. Viscosity:

- The resistance to flow of a fluid and the resistance to the movement of an object through a fluid are usually stated in terms of the viscosity of the fluid.

4. Van Der Waals Bonding:

- Water molecules in liquid water are attracted to each other by electrostatic forces, and these forces have been described as van der Waals forces or van der Waals bonds. Even though the water molecule as a whole is electrically neutral, the distribution of charge in the molecule is not symmetrical and leads to a dipole moment.

5. Brownian Motion.

- Brownian motion originally refers to the random motion observed under microscope of pollen immersed in water. Einstein pointed out that this motion is caused by random bombardment of (heat excited) water molecules on the pollen.
- A suspended particle is constantly and randomly bombarded from all sides by molecules of the liquid. If the particle is very small, the hits it takes from one side will be stronger than the bumps from other side, causing it to jump. These small random jumps are what make up Brownian motion.

6. Surface Tension:

- The cohesive forces between liquid molecules are responsible for the phenomenon known as surface tension. The molecules at the surface do not have other like-molecules on all sides of them and consequently they cohere more strongly to those directly associated with them on the surface. This forms a surface "film" which makes it more difficult to move an object through the surface than to move it when it is completely submersed.
- Surface Tension enables water striders and other insects to walk across the surface of water and enables a needle to float.

7. Surfactants:

Surfactants are **surface acting agents** are stabilizing dispersing agents which prevent particle agglomeration even when a strong magnetic field gradient is applied to the Ferro fluid. They are wetting agents that lower the surface tension of a liquid, allowing easier spreading, and lower the **interfacial tension**.

![Magnetic particles, with surfactant molecules attached, suspended in a fluid to form a Ferro fluid. The surfactant prevents clumping of the magnetic particles. (Drawing courtesy of Ferro Tec Corporation (USA)).](image)

8. Density:

- Density is a physical property of matter, as each element and compound has a unique density associated with it. Density defined in a qualitative manner as the measure of the relative "heaviness" of objects with a constant volume; also refer to how closely "packed" or "crowded" the material appears to be.

9. Colloid

- Colloid is a substance that consists of particles dispersed throughout another substance which are too small for resolution with an ordinary
light microscope but are incapable of passing through a semi permeable
membrane. A colloid is a type of mechanical mixture where one
substance is dispersed evenly throughout another.

10. Agglomeration

➢ Agglomeration, whereby the moist sticky particles collide due to the
turbulence and adhere to each other forming agglomerates, is essential for
the rewet process.

PACING:

This lesson on ‘Ferro fluids’ is introduced using entertaining strategies to elicit students'
natural curiosity and excitement about science with a twist of fun! The lesson begins to
see evidence of magnetic properties in a fluid, explaining it with the help of analogies.
There are extensions recommended at the end of the lesson for further exploration and
expansion of this concept.

Day 1 (30 minutes): Related activities are demonstrated by teacher using students as
they are already familiar with the concepts.

1. Plotting magnetic lines using a bar magnet and a magnetic compass.
2. Observe Brownian motion under a microscope.
3. Observe the surface tension property of water

Here are some ideas for activities involving a Ferro fluid (30 minutes).

1. Use a strong magnet to float a penny on top of the Ferro fluid:

Procedure

• Pour a small amount of Ferro-fluid in a Petri dish, so that the bottom of the
dish is covered.
• Place a penny in the Ferro-fluid in the Petri dish. The penny sinks to the
bottom.
• Bring a strong magnet up **underneath** the container. The attraction of the
Ferro fluid for the magnet forces the penny up and out of the Ferro fluid.
• Repeat this demonstration with water replacing the Ferro fluid to show
that the magnet is not pushing the penny up. The strong attraction between
the Ferro-fluid and the magnet will force a penny up and out of the fluid.

2. Study the surface pattern aligned to the magnetic lines of force:
Procedure

- Place small, powerful magnets in patterns such as letters underneath the Petri dish. The patterns will transfer to the Ferro-fluid.

Place strong magnets in a pattern, such as the "UW" shown.

The magnetic field pattern is manifested in the Ferro-fluid.


Day 2: EXPERIMENT: FERRO-FLUIDS

PURPOSE:

1. To study the viscosity behavior of Ferro-fluids with and without the presence an external magnetic field.
2. To study the viscosity behavior of Ferro-fluids under varied temperatures with and without the presence an external magnetic field.

MATERIALS REQUIRED

Ferro-fluid sample
Graduated cylinder
Glass marble (sphere)
Stop watch
Hot plate
Thermometer
Large Pan (for hot water bath)
Ice
Tongs (for retrieving sphere from heated oil)
Gram scale for measuring mass of oil and sphere

OBJECTIVES

1. To compare the viscosity of Ferro-fluids in the absence of an external magnetic field and under the influence of an external magnetic field.
2. To compare the viscosity of Ferro-fluids when there is a temperature variance, with or without the influence of an external magnetic field.

SAFETY PRECAUTIONS

- Be careful when handling strong magnets such as Neodymium magnets. Don't let them snap to each other because they will chip or break and small pieces will go flying off.
- Wear safety goggles as sometimes the magnets snap to each other resulting in chipping off and the small chips may lodge into the eye.
- Magnets should be allowed to slowly come together, watching that the fingers don't get pinched.
- Magnets should not be dropped as it affects the strength of the magnet.
- Use a hot plate heating the water bath in this experiment, never an open flame.
- The Ferro-fluid causes stains and is difficult to remove from skin and fabrics. Keep the fluid off the magnet. It is virtually impossible to remove Ferro-fluid after direct contact with a strong magnet.

PROCEDURE

1. Measure the time it takes for the sphere to fall through the Ferro fluid.
   a. Pour the Ferro fluid into the graduated cylinder.
   b. Measure the height of the Ferro fluid (in cm).
   c. Hold the sphere (marble) at the surface of the Ferro fluid.
   d. Release the sphere and start the stopwatch at the same instant.
   e. Stop the stopwatch at the instant the sphere touches the bottom of the graduated cylinder.
2. Repeat the measurement several (at least 6) times. Remove the sphere with tongs, allowing the Ferro fluid to drain off. Record the height to make sure of the height for every trial. Record the distance and the time readings in data table-2.
3. Repeat steps 1-2 after placing the neodymium magnet at the bottom of the graduated cylinder and record the readings in the data table - 2.
Day 3:

5. Cool the Ferro-fluid by placing the graduated cylinder containing the Ferro-fluid in an ice bath. Stir the Ferro fluid occasionally to insure uniform temperature. When the temperature of the Ferro fluid is no longer changing, remove the graduated cylinder containing Ferro fluid from ice-bath and repeat the velocity measurement as in step 1 and 2. Follow the same steps to measure time by placing the neodymium magnet under the graduated cylinder. Record temperature, distance and the time in data table –3.

6. Heat the Ferro-fluid by placing the beaker in a pan of water on a hot plate. Do not boil the water bath vigorously. Stir the Ferro fluid occasionally to insure uniform temperature. When the temperature stops changing, remove the graduated cylinder containing Ferro fluid from hot-bath and repeat the velocity measurement as in step 1 and 2. Record the temperature of the Ferro fluid and repeat the velocity measurement as before. Repeat the steps to measure velocity, by placing a magnet under the graduated cylinder. Record all the readings in data table - 3.

7. Calculate the average falling time for each temperature. Calculate the average velocity of the sphere at each temperature. The velocity is the distance that the sphere fell (in cm) divided by the average time it took to fall (in s).

8. Calculate the density of the sphere. Density is mass per unit volume, in g/cm³. Measure the mass of the sphere in grams. To measure the volume of a sphere, measure how much water the sphere displaces in a graduated cylinder. The difference in the water level will be the volume of the sphere. (The volume of the sphere 4/3πr³ relationship can also be used after determining ‘r’ value of the sphere).

9. To measure the density of the Ferro-fluid, first measure the mass of the empty graduated cylinder. Then pour oil into the cylinder and weigh the cylinder and Ferro-fluid together. Subtract the mass of the empty cylinder to get the mass of the Ferro-fluid. Record the volume of Ferro-fluid. Calculate the density using the formula mass/volume. Record the readings in data table-1.

10. Use Equation 1 to calculate the viscosity of the Ferro fluid at each temperature.

\[
\text{viscosity} = \eta = \frac{2(\Delta \rho)ga^2}{g \nu}
\]  

a. \(\Delta \rho\) = density of the sphere − density of the Ferro-fluid (in g/cm³),
b. \(g\) = acceleration due to gravity (980 cm/s²),
c. \(a\) = radius of the sphere (in cm),
d. \(\nu\) = average velocity of the falling sphere (in cm/s).
e. \(\eta\) = (eta) viscosity in poise (g/cm·s).
### Data Table 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>Free fall acceleration</td>
<td>$980 \text{ cm/s}^2 = 9.81 \text{ m/s}^2$</td>
</tr>
<tr>
<td>a</td>
<td>Radius of the glass marble</td>
<td>$\text{cm} = \text{m}$</td>
</tr>
<tr>
<td>$\Delta \rho$</td>
<td>Difference in Densities, $\rho_1 - \rho_2$</td>
<td>$\text{g/cm}^3 = \text{Kg/m}^3$</td>
</tr>
<tr>
<td>$m_1$</td>
<td>Mass of marble</td>
<td>$\text{g} = \text{kg}$</td>
</tr>
<tr>
<td>$v_1$</td>
<td>Volume of marble, $v = \frac{4}{3} \pi r^3$</td>
<td>$\text{m}^3$</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>Density of marble, $m/v$</td>
<td>$\text{Kg/m}^3$</td>
</tr>
<tr>
<td>$m_2$</td>
<td>Mass of Ferro fluids</td>
<td>$\text{g} = \text{kg}$</td>
</tr>
<tr>
<td>$v_2$</td>
<td>Volume of Ferro fluids</td>
<td>$\text{cm}^3 = \text{m}^3$</td>
</tr>
<tr>
<td>$\rho_2$</td>
<td>Density of Ferro fluids, $m/v$</td>
<td>$\text{g/cm}^3 = \text{Kg/m}^3$</td>
</tr>
</tbody>
</table>

### Data Table 2: To determine velocity

<table>
<thead>
<tr>
<th>Trials</th>
<th>Distance (cm)</th>
<th>Time (s)</th>
<th>Velocity (cm/s)</th>
<th>Distance (cm)</th>
<th>Time (s)</th>
<th>Velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>6</td>
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<tr>
<td>Average Velocity</td>
<td></td>
<td></td>
<td></td>
<td>Average velocity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Data Table 3

<table>
<thead>
<tr>
<th>Trials</th>
<th>Temp ($^\circ$C)</th>
<th>In the absence of an external magnetic field</th>
<th>In the presence of an external magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distance (cm)</td>
<td>Time (s)</td>
<td>Velocity (cm/s)</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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</tbody>
</table>
ANALYSIS /CONCLUSION

1. Calculate and compare the viscosity obtained from data table 2 and interpret your answer. Convert the viscosity to SI units. Show all your work.
2. Explain how the external magnetic force has affected the viscosity of Ferro fluid?
3. Calculate and compare the viscosity obtained from data table 3 and interpret your answer. Convert the viscosity to SI units. Show all your work.
4. Account for the variation in viscosities in terms of difference in temperatures, with and without the presence of an external magnetic field.
5. Make a bar graph of falling time (in seconds, on the y-axis) vs. temperature of the oil (in °C), on the x-axis. Interpret your graph.
6. Make a bar graph of falling time (in seconds, on the y-axis) vs. viscosity of the Ferro fluids, on the x-axis with and without external magnetic field. Interpret your graph.

RUBRICS

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Points</td>
<td>4 Points</td>
<td>10 Points</td>
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<tr>
<td>4 Points</td>
<td>10 Points</td>
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<tr>
<td>20 points</td>
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</table>

Participation in the brainstorm activity and demonstration activities.

Setting up the lab equipments, following lab safety, and sharing responsibility by all team members while performing the lab.

Drawing data table, showing step-by-step calculations and correct representation of units.

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Drawing data table, showing step-by-step calculations and correct representation of units.

Answers to questions including interpretations, graphing, and conversion calculations.
EXPANSION/ENRICHMENT SUGGESTIONS

The following websites will provide further information on different types of activities and interesting videos.

- http://www.educatedearth.net/video.php?id=2927 – to get two dimensional magnetic lines and surface patterns.
- http://www.eng.yale.edu/koserlab/Ferrofluid_background.html
  1. The unit can be extended by including the research paper on the applications of Ferro-fluids.
  2. Students can be made to synthesize their own Ferro-fluid in the lab using available lab chemicals. Step-by-step procedure is illustrated in the following website:

REFERENCES

- http://www.coolmagnetman.com
- http://www.eng.yale.edu/koserlab/Ferrofluid_background.html
- http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TFR-47VS66F-2&_user=10&_rdoc=1&_fmt=&_orig=search&_sort=d&_view=c&_acct=C000050221&_version=1&_userid=10&md5=082f6bcd3ac3503348ed23c7c5

Ferro fluid and magnets are available at:

- http://www.emovendo.net/
- http://www.magnet4less.com
- http://www.amazingmagnets.com/inde
- http://www.ferrotec.com/products/ferrofluid/?_kk=ferrofluids&_kt=671988ba-d0a9-440d-992c-89e0093f0bda&gclid=CIPKjpqU1pQCFQWxsgodG0wulg