A Thesis

entitled

Post-Consumer Plastic Particle Sortation by Plastic Type with the Use of Magnetic Fields and Ferrofluids for the Recycling Industry: A Proof of Concept Study

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in Mechanical Engineering

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An Abstract of
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In 2010, the United States generated over 31 million tons of plastic waste, and from that total, only 8% was recycled. With demand for lower cost plastics and public attention to environmental concerns increasing, the expanding recycling industry has provided an opportunity to lower raw material costs and create new jobs. Traditionally, manual or optical methods that used infrared technologies were utilized to sort plastic wastes for recycling. Once these plastic wastes were sorted, they were cleaned, shredded, and melted into raw materials. These methods are costly and can experience high nonconformance rates during the sortation processes. This thesis discusses an emerging technique that utilizes a novel process that sorts shredded plastic particles by using electromagnetic (EM) waves and Ferro fluids. The process involves placing various types of shredded plastic particles of into a tank filled with ferrofluid. The plastic particles and ferrofluid are then subjected to an EM wave by the use of an EM coil. The EM wave alters the density of the ferrofluid and causes the shredded plastic particles to rise and sink at different vertical levels within the ferrofluid tank, based on the plastic particles’
respective densities. This method allows for an efficient, accurate, and low cost method to sort plastic particles as compared to conventional technologies. Overviews of the model development, experimental design, and test results are provided that demonstrates proof-of-concept. The results of the study indicated that the EM separation method may offer significant cost, efficiency, and accuracy improvements over conventional methods.
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List of Abbreviations

Al..............................Aluminum
DAQ..........................Data Acquisition
DC............................Direct Current

Mn............................Manganese
MSDS........................Material Safety Data Sheet

PET..........................Polyethylene Terephthalate
PVC..........................Vinyl / Polyvinyl Chloride

Si............................Silicon
List of Symbols

% .................................Percentage

π .................................Pi (3.14159…)
ρ .................................Rho (Density)
μ₀ .................................The Permeability of Free Space

B .................................Magnetic Field
C .................................Degrees Celsius
F .................................Degrees Fahrenheit
I .................................Current
P .................................Pressure
R .................................Universal Gas Constant
T .................................Temperature
V .................................Volume

a .................................Distance from a Wire
d .................................Diameter
n .................................Number of Moles
r .................................Radius
Chapter 1

Introduction

1.1 Importance of Research

Since 1960, the US Gross Domestic Product has increased from $520.5 billion to $15.7 trillion in 2012 [1]. During this same timeframe, waste generation in the United States has increased from 88.1 million tons to 249.9 million tons [2]. As the United States has grown more productive, and as more goods are consumed, more waste is being generated. In order to handle this increased waste generation improved methods and technologies are required. Recycling is becoming ever important as well due to space constraints and the use of finite resources for the production of goods. An extreme example of the problems that can arise from insufficient landfill space is the waste problem in the town of Naples, Italy. Due to landfills being closed over the years as a result of protests and organized crime, Naples only had one operating landfill as of 2008. This single landfill was able to accept 2,000 tons of refuse per day; not nearly enough capacity to handle all of the waste generated in Naples. This caused a significant backup of waste that needed to be collected and some residents resorted to burning their garbage [3]. While it may seem improbable for this same problem to arise in the United States, it is certainly
possible due to increased population and increased waste generation. A higher rate of recycling is a tool that can be used to combat these types of problems. If the scale of recycling in the United States is to increase, the recycling industry and technology will need to advance as well.

Of the products that are recycled from the waste stream, plastic is of significant importance. Plastic refuse is problematic for society and has experienced low recycling rates. For example, the United States generated 31.84 million tons of plastic waste in 2011 and of that total, only 8.3% was recycled [2]. Compare this with other commonly recycled materials such as glass and aluminum which were recycled at rates of 27.6% and 20.7% respectively. Getting the recycling rate of plastic up to a similar level could triple the amount of plastic that is recycled. With increasing demand for lower cost plastics and heightened public attention to environmental concerns, the expanding recycling industry has provided an opportunity to lower raw material costs and create jobs. This is expected to be greatly influenced by the United States’ Recycling Works Program.

The Recycling Works Program is a recycling initiative which establishes a 75% solid municipal waste recycling goal by the year 2015 [4]. While a recycling rate of 75% may sound unattainable as the current national recycling rate is about 33%, some states and cities show that there is a great deal of room for improvement. For example, San Francisco has a recycling rate of 70%, and the state of California itself has a recycling rate of 58%. In contrast to these areas with high recycling rates there are eleven states with recycling rates below 10%. The program also sets a National Manufacturing Reuse Goal of 30% by the year 2020. This reuse portion of the program helps to ensure that there is a sufficient market for the increased generation rates of recycled materials that
would result from attaining a 75% solid municipal recycling rate. The reuse goal is very important because increasing the recycling rate to 75% without actively trying to increase the market for recycled materials would likely result in failure. The market would become saturated with recycled materials and their value would drop drastically. This program sets the precedent for major growth in the recycling industry over the next several years. Along with possible subsidies from the federal government, the program is expected to generate 1.5 million new jobs in both recycling and post-manufacturing waste recovery [4]. Modern technologies can be difficult to cost justify in waste processing due to the need for large capital investments. If federal and state governments subsidized capital for these operations, it may significantly influence their adoption. With this potential large increase in recycling levels, the recycling industry would benefit from a technology that can quickly and cheaply sort plastic.

1.2 Objective

The primary objective of this research is to provide proof of concept for a new plastic sortation technique that utilizes ferrofluid and electromagnetic (EM) waves as the primary mechanism for sortation. The process involves placing various types of shredded plastic particles into a tank filled with ferrofluid. The plastic particles and ferrofluid are then subjected to an EM wave generated through the use of an EM coil. The density of the ferrofluid can be changed by the EM wave. By altering the density of the ferrofluid, different types of plastic can be made to float to the surface of the fluid where they can then be skimmed off as the means of separation. This method allows for an efficient, accurate, and low cost method to sort plastic particles as compared to conventional
technologies. The use of EM waves to sort metal scrap has been applied previously in the recycling industry, to sort aluminum scrap [5, 6] and for the elimination of non-ferrous scrap using electromagnetic filtration [7]. This study expands the use of EM waves in the recycling field to a new application and process related to plastic materials.

Following successful proof of concept, the research will be further developed. In theory, this method would prove to be more cost effective and efficient at plastic sortation versus existing technologies. A larger scale prototype may then be constructed to conduct further testing.

1.3 Literature Review

1.3.1 Plastic Sortation Methods

In order to evaluate this new method of plastic sortation it is important to compare it to current methods that are in use by industry. There are five current methods that will be analyzed for comparison. These methods are known as electrostatic separation, the sink/swim differential method, surfactant based separation, near-infrared scanning, and ultrasound scanning. The method that is the main focus of this report will be referred to as the ferro-EM method. This section will provide some information on the current plastic sortation methods that are in use.

1. Electrostatic Separation

This technology was developed in the 1990’s as an example of an electrically based solution to sorting plastic [8]. Through statically charging particles using friction, then
exposing them to an electrostatic field, an electromotive force is induced. The particles are then sorted based on their charges.

A simple triboelectric separator consists of six components: a feeder system, a blower, a cyclone shaped tunnel for the triboelectric friction to occur, assorted containers for collecting sorted plastic bins, and two vertical-plate electrodes along with their accompanying DC power supply [8]. The triboelectric separator is typically installed with a climate control system, which regulates temperature and humidity. In operation, the feed is distributed in a current of air provided by the blower and introduced into the cyclone through its tangential entry. The air current is used to accelerate the mixture into the cyclone and rub it against the inner lining. After a certain period of frictional charging time, the oppositely charged plastics fall down freely in the area between the electrodes. The particles are drawn to either the positive or negative electrode according to the polarity of the charge, and separated by falling in different collecting bins.

2. Sink/Swim Differential Method

The method of sink/swim sorting of plastics is one of the older procedures used for recycling [9]. The principle is very simple; mix the plastics in a large container filled with a liquid of known density. After some time, the plastics will either float or sink based on the density. This has been used since the 70’s and is a well-documented technique [9]. In recent years, the system has grown largely in scale, due to increasing demands and further technological advancement of the practice.

Although this method is very straightforward in concept, the mechanics could be considered complex. Ideally, all of the plastic variations involved have prominent
differences in density. The larger the contrast, the more accurately the plastic is sorted. Unfortunately, waste plastic densities do not differ significantly, as displayed in Table 1 [10].

<table>
<thead>
<tr>
<th>Material</th>
<th>Density Range (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>0.916-0.925</td>
</tr>
<tr>
<td>Low-Density Polyethylene</td>
<td>0.936-0.955</td>
</tr>
<tr>
<td>High-Density Polyethylene</td>
<td>0.956-0.980</td>
</tr>
<tr>
<td>Bulk Polystyrene</td>
<td>1.050-1.220</td>
</tr>
<tr>
<td>Polyvinyl Chloride</td>
<td>1.304-1.336</td>
</tr>
<tr>
<td>Polyethylene Terephthalate</td>
<td>1.330-1.400</td>
</tr>
</tbody>
</table>

In recycling, there is a narrow window for the process to work, so often containers are pressurized [11]. This allows for slight changes in pressure, which can be used to slightly change the density of the fluid. The ability to control the density of the fluid creates a large amount of regulation over the process. By having an exact value of the density of the liquid in relation to the desired plastic being sorted, much more accurate sortation is attainable. A simple computer based algorithm can separate the waste plastics by changing the pressure in the tank. This also significantly reduces the likelihood of having to employ different types of liquids in order to isolate dissimilar plastics.

3. Surfactant Based Separation

Surfactants are also used to sort plastics on a large scale. This method is similar to the sink/swim differential method. When using this technique, the materials to be separated are first treated with a surfactant and then suspended in water [11]. Because of a reaction with the surfactant material, plastics that would normally sink in water are suspended in
the mixture. Air is then introduced into the system via pump. The air bubbles adhere to some particles depending on their resin type, causing the particles to float to the surface. Materials that are not affected by the bubbles sink to the bottom. Collection systems at the top and bottom of the tanks can then collect the now isolated materials.

The first noticeable benefit is that no advanced technology is essential. Second, the chemicals used are common in chemical processing and do not pose any substantial environmental hazards. Third, froth-flotation can separate certain plastics, such as PET from PVC, which has instituted a crucial problem to the conventional sink-float separation establishments.

4. Near-Infrared Scanning

Infrared scanning of plastics is an existing technology in the recycling community, and has become one of the most common methods of sorting plastics [12]. It’s used to sort nearly every type of plastic, and it can operate at large volumes. Using infrared scanners, the plastic is examined, and then it removed from the feed.

Infrared scanning operates on the concept that plastics can be analyzed using near-infrared scans that examine both density spectrometry and resin color [11]. It recognizes the density spectrometry by exposing the plastic sample to infrared light, then processing the returning wavelength [13]. It also uses simple high speed cameras to look for resin color. After identifying the type of plastics, it is marked optically, then that plastic is then removed from the system. Typically this is done instantly using compressed air to push the plastic off the line. During operation, the line moves rapidly,
using an advanced computer system to track the plastics until their eventual removal from the machine [13].

5. Ultrasound Scanning

Ultrasonic scanning of plastics for recycling purposes is a more recent practice to the marketplace. This technology sorts plastics using ultra-sonic waves in water to determine density of plastic samples. The plastics are then removed from the processing line based on the results. This is typically done using mechanical arms to grab plastics and is a highly technical method of sorting. Ultrasound scanning uses some of the same routes of technology utilized by other scenarios. Unlike other technologies, however, it can accurately describe plastic densities in non-clear liquids, such as ferrofluid, whereas many optical methods would be useless. The ultrasound scanning method also builds a 3D-image of the objects, something which no other technology has employed.

1.3.2 Investigation of Related Technologies

Past research and work on the topics of electromagnetism and ferrofluids were examined for the insight and expertise they could provide for this project. Past work that pertained directly to the recycling industry was of particular importance. A few of the topics that were investigated are explained in detail below.

A method of sorting scrap nonferrous metals has been developed that utilizes both an electromagnetic sensor and a dual energy X-ray transmission sensor [5]. An electromagnetic sensor is able to sense the interaction between a piece of metal and the electromagnetic field it has been subjected to. By sensing this interaction the sensor is able to determine the electrical conductivity of the metal. This value for electrical
conductivity can then be used to sort various types of metal. Some metals will have very similar values for electrical conductivity when analyzed using this sensor. It is for this reason that an electromagnetic sensor was combined with a dual energy X-ray transmission sensor. The X-ray sensor is able to analyze the atomic number of a material. The combination of an X-ray sensor along with an electromagnetic sensor allows for more accurate metal sortation.

Research has also been done on a method of sorting nonferrous metals from other nonmetallic materials by subjecting the materials to a high-frequency electromagnetic field [6]. This method would be useful in the separation of electrical scrap. For example, electrical wire is usually made up of a copper core which is surrounded by an insulating material. The copper core is valuable and therefore wiring is worth recycling. The challenge is finding a cost effective way or separating the valuable metal components from the rest of the material. When the mixture of materials is subjected to a high-frequency electromagnetic field as suggested in this report, the electrically conductive particles experience a change in trajectory while the materials with low or no electrical conductivity remain on the same path. This is a fast and novel method of separating nonferrous metals from other nonmagnetic materials.

The final research report on the use of electromagnetism for sortation or separation that was investigated pertained to the use of electromagnetic field to reduce iron levels in Al-Si alloy [7]. Iron is becomes present in the alloy when Mn is added to the melt. Applying an electromagnetic force to the melt allows the iron to be separated from the Al-Si alloy. This process lowered the iron content in the alloy from 1.20% to 0.41%.
Previous work relating to the use of ferrofluids for material separation was also investigated. One such paper that was examined pertained to the use of magnets and ferrofluid in a sink/swim separator [9]. The idea behind this research was to design a permanent magnet that provides a field of reduced intensity that can be used in combination with a ferrofluid to form a magnetic density separator. This research found that the density of the ferrofluid is comparable to the density of polymer. This allows the use of relatively low-intensity magnetic fields for polymer separation. The report also mentions that electromagnets could be used in place of permanent magnets. The method which this thesis is concerned with utilizes an electromagnet which allows for the density of the ferrofluid to be actively changed in order to separate plastics.
Chapter 2

Materials and Methods

2.1 Ferrofluid

A ferrofluid is a fluid in which fine particles of iron, magnetite or cobalt are suspended, typically in oil, and can be manipulated with magnetic fields [14]. The typical size of the suspended iron particles are in the nanometer range, but for this application a micrometer range will be used as larger particles tend to respond better to a magnetic field. When the fluid is subjected to an electromagnetic wave, the iron particles align and the viscosity changes.

Ferrofluid is a liquid that can be manipulated with magnetic fields. For this experiment, it will act as the fluid displaying variable viscosity. Ferrofluids are colloidal liquids composed of suspended ferromagnetic particles in a carrier liquid. Typically the carrier liquids are oils, water, acids, or organic solvents. In this suspension, the addition of a surfactant prevents the ferric particle from binding to each other. When the ferrofluid is exposed to a magnetic field it will align and form temporary domains in the system. These temporary domains alter the viscosity of the ferrofluid. Although the ferrofluid is magnetically active while being exposed to EM fields, it will immediately lose those
properties after the field is removed. This material property is called colloidal liquidity, and it is this property that allows for this method of plastic sortation. The ability of ferrofluids to change material properties when exposed to electromagnetic pulses allows for near complete control of the material. This control is possible in part to the relatively small particle size of the ferromagnetic particles in the ferrofluid. For this experiment, the research team examined ferrofluid with a particle diameter in the micrometer range; technically this means the fluid is categorized as a magnetorheological fluid. A ferrofluid typically has a diameter in the nanometer range. It is known that the larger particles respond with better results to magnetic fields.

**2.2 Material Properties of Ferrofluid**

The most critical property of the ferrofluid to be useful in plastic separation is its specific gravity. In order to control which plastic will rise to the top of the solution, the density of the fluid must be altered to values that lie between the specific gravities of differing plastics. Table 2-1 shows the different types of recycled plastics and their corresponding specific gravity values.

<table>
<thead>
<tr>
<th>Plastic Type</th>
<th>Specific Gravity (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyolefins</td>
<td></td>
</tr>
<tr>
<td>Polypropylene</td>
<td>.916-.925</td>
</tr>
<tr>
<td>Low-density Polyethylene</td>
<td>.936-.955</td>
</tr>
<tr>
<td>High-density Polyethylene</td>
<td>.956-.980</td>
</tr>
<tr>
<td>Non-olefins</td>
<td></td>
</tr>
<tr>
<td>Bulk Polystyrene</td>
<td>1.050-1.220</td>
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<tr>
<td>Polyvinyl Chloride</td>
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</tr>
<tr>
<td>Polyethylene Terephthalate</td>
<td>1.330-1.400</td>
</tr>
</tbody>
</table>
According to the MSDS sheet for the ferrofluid, there is a density range of 0.92 g/cm^3 to 1.47 g/cm^3 with a specific density of 1.21 g/cm^3 at 25 degrees Celsius. Using a digital scale and an accurate graduated cylinder, the density can effectively be calculated. For this experiment, the specific gravity of the sample ferrofluid was 1.15g/cm^3 at 25 degrees Celsius.

For this experiment, the research team correlated the magnitude of field intensity to the dynamic viscosity. In order for any given plastic to float in the solution, the specific gravity of the ferrofluid must be greater than that of the plastic. Based on this assumption, it was concluded that an 11% change in specific gravity is necessary in order to produce the desired effect of separating plastic waste.

### 2.3 Electromagnetic Core

In order to ascertain whether ferrofluid has any sort of measurable response to magnetic waves it is necessary to devise a method to reliably generate a magnetic field. In deciding what equipment to use to make this generation possible, a set of design criterion was laid out. These design qualifications included the ability to vary performance characteristics, the existence of experimentally tested mathematics, as well as a set of feasibility checks which included cost, manufacturability, and speed of delivery.

Upon investigation it was decided that a small, iron cored electromagnet was the best fit for the project. An iron core electromagnet is easily customized through changes in radius, length and number of turns, has a well-developed set of equations for various design types and can be manufactured with relative ease. A picture of the completed electromagnet as a component of the test setup can be seen in Figure 2-3.
2.4 Material Properties of the Test Vessel

The type of plastic chosen to contain the ferrofluid was antistatic acrylic. It was chosen for its ability to resist the building of static charge [15]. If the box was not antistatic then the acrylic would absorb charge. This charge could potentially become large enough to create voltage that could be hazardous to both equipment and/or people. If the box were to build charge on the surface then the EM waves and the ferrofluid could be affected. Careful control of the EM waves is imperative in controlling and understanding how the ferrofluid reacts in the given field. Additionally, some of the data acquisition was done digitally; this plastic will reduce the chance of a stored charge causing a voltage change, altering the data.

This particular acrylic was also chosen because of its inherent resistance to deflection that could be caused by a net change of pressure in the box. The acrylic is ideal for use in a pressure vessel. When this experiment was being designed, it was not yet determined whether or not a net pressure would occur, therefore causing the overall density of the ferrofluid to fluctuate based on the relative pressure change.
After designing and building the pressure vessel, the team conducted a static pressure test to determine the sealing capability of the vessel. Figure 2-1 displays the results for pressure loss over time using the largest theoretical pressure based on the design of the vessel. This loss is roughly 1 psi loss over 6 minutes, or 0.0028 psi per second. For a typical test that occurs in less than 20 seconds, and has a pressure change of less than one psi, the team determined this pressure vessel is sufficiently sealed, and deemed it an acceptable standard for testing.
2.5 Pressure Data Acquisition

A change in density of the ferrofluid could not be measured directly. Upon initial research, the team applied the ideal gas law to prove that there is indeed a density change by logging a pressure change. The two variables are related by the following function displayed in Equation 1:

$$\frac{p}{\rho} = R \times T$$

Equation 2.5-1

In equation 2.5-1, T is temperature, P is pressure, \(\rho\) is density, and R is the ideal gas constant. Assuming that the temperature is constant along with R, density will change inversely with pressure. Since the system will be closed and the box is rigid, the volume will not change by any significant amount. It is hypothesized that the excitation of the
ferrofluid by EM waves will cause the density of the fluid to increase. This will decrease the volume of the fluid causing a vacuum to be created in the air. Therefore, the team had to design a data acquisition system that would account for this negative pressure change in the air.

Two methods were proposed to measure the vacuum effect. One was the use a mechanical vacuum gauge, while the other was the idea to use a digital manometer. The mechanical vacuum gauge seemed like the likely solution because the effects from EM waves on a digital system were unknown. The team was concerned that the magnetic flux would induce a current and skew the data. However, all of the vacuum gauges that the team found used mercury to detect and scale the pressure change. Mercury is slightly magnetic and could skew the data by a large percentage since the anticipated pressure change is so small. Research done prior to the project being handed off to the team found that in the closed system contained with the aforementioned box the pressure change should be very minimal (around 1 psi). The final solution was to use a digital manometer offset from the system, making the effect from the EM waves negligible. The digital manometer is also far more accurate than the mechanical vacuum gauge.

Furthermore, a pressure transducer was placed into the ferrofluid to examine the change in specific gravity in real time. This pressure transducer was selected on the basis of the following characteristics. Firstly, it is waterproof and highly resistant to acidic decay, as some ferrofluids are slightly acidic. Secondly, this pressure transducer is also bidirectional; this allows a dynamic response to the ferrofluid to be ascertained when it exposed to an electromagnetic pulse. Thirdly, this device produces a varying signal based
on voltage, not current. Combined with a calibrated data acquisition system, a detailed pressure change could be pictured accurately.

### 2.6 Magnetic Field Sensor

For the experiment, two magnetic field sensors were determined to be needed in order to quantify the strength of the field propagated throughout the system. The effect on the digital measurement system is unknown so some sort of calibration is necessary. One sensor will be placed just under the coil and the other will be placed directly opposite on the other side of the box. Before testing occurred, a series of tested were conducted to find a relationship between the magnetic field strength and the amount in which the digital measurement systems are affected in order to increase accuracy.

For this experiment the research team chose to use Passport magnetic sensors. These sensors are pre-calibrated and consist of a sensor in a housing that allows for easy use and high quality data. Additionally, this system also allows multiple sensors to allow for greater data stream to confirm static conditions as well as a comparison for calibration of instrumentation in the NI system.

### 2.7 Software

In this experiment, two type of software were to be used. The software for stage one will be Labview, the accompanying software of the National Instruments data acquisition system. In our experiment a Series X DAQ box was used. The data acquisition system is USB based and allows for a relative simple and inexpensive setup yet produces a high quality of accuracy. This system was also chosen on because of it closed metal
frame/chassis that allows for radiant electromagnetic energy to be dissipated safely through a ground. The DAQ was used to collect data, and analyze it for material qualities.

Calibration of the system was conducted within 24 hours of experimentation in order to lower the likelihood of a calibration error. For the pressure transducer, the manufacturer had pre-calibrated the device. The research team also confirmed this basis by testing at 1 atmosphere. Additionally; the research team applied a secondary calibration by using a different device, a Passport absolute pressure gauge. Both of these methods yielded near exact calibration for testing the pressure. Calibration for each k type thermocouple was achieved by recording variation from temperatures ranging from 33 degrees F (ice bath) to 214 degrees F (boiling water). The handheld thermometer and an infrared optical temperature measurement device seconded these results. These two measurement devices can be seen in Figure 2-3.

2.8 Experimental Setup

Figure 2-2 is an image of the setup that was used when testing was conducted. Every component of the system is numbered with a corresponding description below.
1. Solenoid Design
2. Pressure Vessel
3. Ferrofluid
4. Pressure Data Acquisition
   a. Manometer
   b. Pressure Transducer
5. Thermal Data Acquisition
6. Magnetic Field Sensor

Figure 2-3 – Experimental Setup [15]
Chapter 3

Theory and Calculations

3.1 An Introduction to Electromagnetic Physics

In simple terms, the idea behind electromagnetism is that current travelling through a wire can be used to induce a magnetic field. The large electromagnets that are used to pick up cars in junk yards may be an example that is familiar to many people. In a straight wire with a current flowing through it the magnetic field that is induced is in the shape of concentric circles down the length of the wire. These magnetic fields are illustrated in Figure 3-1.

Figure 3-1 – Magnetic Field Lines [17]
In Figure 3-1, “I” represents the current in the wire and “B” represents that magnetic field that is induced in the wire. In a system such as the one presented in Figure 3-1, the magnetic field at a distance away from the wire can be calculated using the following equation [17].

\[ B = \frac{\mu_0 I}{2\pi a} \]  

Equation 3.1-1

Where:

- \( B \) = Magnetic Field (tesla)
- \( I \) = Current (amperes)
- \( a \) = Distance from the Wire (meters)
- \( \mu_0 \) = The Permeability of Free Space

This concept of a magnetic field being induced by an electric current in a wire was used to design a solenoid. The solenoid will act as the electromagnet which is used to control the ferrofluid in the system.

### 3.2 Solenoid Design

The concept of a solenoid is similar to the concept of a magnetic field being created by an electric wire. In the case of a solenoid the wire is formed into a specific shape to achieve the desired result. A solenoid consists of a wire which is wound into tightly packed coils. For the solenoid used in this experiment the wires were wrapped around an iron core. The
use of a solenoid allows for a uniform and controllable magnetic field. The magnetic field of a solenoid is explained by the following equation and figure [18].

\[
B = \frac{\mu_0 \mu_r i}{2d} \left( \frac{x_2}{\sqrt{x_2^2 + r^2}} - \frac{x_1}{\sqrt{x_1^2 + r^2}} \right)
\]

Equation 3.2-1

Figure 3-2 – Single Layer Iron Cored Solenoid

Where:

\[
\mu_0 = 4\pi \times 10^{-7} \frac{H}{m}
\]

\[
\mu_r = 2425
\]

\[
i = 4 \text{ Amperes}
\]

\[
d_{12 \text{ AWG wire}} = 0.002053 \, m
\]

\[
x_1 = 0.025 \, m
\]

\[
x_2 = 0.225 \, m
\]

\[
r = 0.02 \, m
\]
From the equation above the calculated strength of the electromagnet is 0.64 tesla or approximately 6,400 gauss. This is roughly 10 times the amount of magnetic field intensity needed for the saturation of the ferrofluid given the ferrofluid requires 650 gauss to become excited. A strong magnetic field was desirable because of the expected loss of intensity resulting from the rapid change in magnetic field. This loss is referred to as attenuation. Attenuation is commonly found when solenoids use an alternating current to manipulate magnetic field at the frequency of current. Although this loss is well documented, attenuation could not be calculated because of the complexity of induction between the core and ferrofluid.
Chapter 4

Results and Discussion

4.1 Experimental Results

To test for a pressure change it was decided that tests would be conducted at three different voltage inputs. These inputs, being the same as static testing mentioned earlier, were 5.4V, 10.3V, and 14.4V. These values were selected based on previous literature studies related to EM waves and ferrofluids [5-7] and capabilities of the test equipment. Two tests were conducted at each input with a sample size of 1,000 and a sample rate of 100 samples per second. The first 5 seconds were measurements recorded during EM exposure, and the last 5 seconds were at ambient conditions. To gather useful data and to help reduce the error from noise, the average of all data points during EM exposure in both tests were calculated. This same step was done for ambient conditions of both tests at each input. The pressure change of the ferrofluid can be determined by taking the difference of these values. Figures 4-1, 4-2, and 4-3 below depict the test data for 5.4V, 10.3, and 14.4V input respectively. At a 5.4 V input, the mean pressure difference was 0.32246 psi.
Figure 4-1 – Ferrofluid Pressure 5.4V Input [16]
At a 10.3 V input, the mean pressure difference was 0.6135 psi. Note in Figure 4-2 below that the power supply to the EM coil in test two was terminated just over 1 second into testing. The data collected was still deemed useful and a mean was taken for that short interval.

Figure 4-2 – Ferrofluid Pressure 10.3V Input [16]
At a 14.4 V input, the mean pressure difference was 0.6724 psi.

A similar method was used when examining the temperature data. The temperature in the coil rose during testing. At worst case scenario, a 14.4V input, caused the coil temperature to rise to 211°F. A redesign of the coil for future studies would prevent such a temperature rise by changing the wire gauge to lower the resistance of the metal used to create the coil. Although the coil did reach temperatures that may be deemed as harmful, the main concern still resided with the ferrofluid and the air within the container. The air and ferrofluid within the chamber remained at a constant temperature throughout all of the testing. The temperature readings for all of the sensors can be seen in Figure 4-4 below.
To show that the ferrofluid saw no hazardous or significant rise in temperature a 20 second test was done, as can be seen in Figure 4-5. EM exposure was induced at intervals 0-5 and 10-15 seconds, and ambient conditions were upheld at intervals 5-10 and 15-20 seconds. Due to the amount of noise caused by the EM, ambient conditions were deemed as the only useful data when measuring temperature.
The mean temperature over the 5-10 second interval was $72.752 \, ^\circ F$ and at interval 15-20 it was $73 \, ^\circ F$. This showed a total temperature change of $0.248 \, ^\circ F$ in the ferrofluid. This proved that the ferrofluid and air would see no significant temperature rise that may diminish the properties of the ferrofluid or create a harmful environment. This also allowed us to determine temperature as a constant throughout testing and look only at the change in pressure when determining a change in the density of ferrofluid.

Now that the team proved that temperature was constant, and the bulk of the alteration in ferrofluid density was caused by pressure changes, the density change could now be calculated. Though the ideal gas law and reducing the equation we can find a ratio as seen by the following equation.

$$\frac{P_{EM}}{\rho_{EM}} = \frac{P_{\infty}}{\rho_{\infty}}$$

Equation 4.1-1
\[
\rho_{EM} = \rho_{\infty} \left( \frac{P_{EM}}{P_{\infty}} \right)
\]

Equation 4.1-2

Where:

- \( P_{EM} \) is the pressure during EM exposure
- \( \rho_{EM} \) is the density during EM exposure
- \( P_{\infty} \) is the pressure during EM exposure
- \( \rho_{\infty} \) is the density during EM exposure

\( \rho_{\infty} \) was determined to be 1.157 g/cc through measurements. \( \rho_{EM} \) will depict the density of ferrofluid during EM exposure which is equal to \( \rho_{\infty} \) multiplied by the pressure ratio of the EM pressure over ambient pressure. This method of calculating density was done for all tests and can be seen in Table 2 below.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Volts</th>
<th>( P_{EM} ) (psi)</th>
<th>( P_{Am} ) (psi)</th>
<th>( \rho_{Am} ) (g/cm(^3))</th>
<th>( \rho_{Em} ) (g/cm(^3))</th>
<th>( \Delta\rho ) (g/cm(^3))</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>5.4 V</td>
<td>14.6651</td>
<td>14.7549</td>
<td>1.157</td>
<td>1.149957</td>
<td>0.007042</td>
<td>0.60867</td>
</tr>
<tr>
<td>Static</td>
<td>10.3 V</td>
<td>14.5248</td>
<td>14.7622</td>
<td>1.157</td>
<td>1.138388</td>
<td>0.018611</td>
<td>1.60862</td>
</tr>
<tr>
<td>Static</td>
<td>14.4 V</td>
<td>14.5249</td>
<td>14.7889</td>
<td>1.157</td>
<td>1.136344</td>
<td>0.020655</td>
<td>1.78525</td>
</tr>
<tr>
<td>Dynamic</td>
<td>5.4 V</td>
<td>14.0298</td>
<td>14.3522</td>
<td>1.157</td>
<td>1.131005</td>
<td>0.018953</td>
<td>1.63809</td>
</tr>
<tr>
<td>Dynamic</td>
<td>10.3 V</td>
<td>13.7769</td>
<td>14.3904</td>
<td>1.157</td>
<td>1.107676</td>
<td>0.030711</td>
<td>2.65439</td>
</tr>
<tr>
<td>Dynamic</td>
<td>14.4 V</td>
<td>13.7313</td>
<td>14.4038</td>
<td>1.157</td>
<td>1.102985</td>
<td>0.033359</td>
<td>2.88326</td>
</tr>
</tbody>
</table>

There were three static tests and three dynamic tests that were tabulated. This table displays the input voltages, pressure values, and initial densities. These were then used to calculate the density during EM exposure. The real significance lies within the density change. During static testing, which was done for calibration purposes, density...
changes of 0.007042 g/cc, 0.01861 g/cc, and 0.020655 g/cc were experienced at 5.4V, 10.3V, and 14.4V inputs respectively. By taking the calculated mean pressure differences in Figures 4-1, 4-2, and 4-3 on the previous pages and then subtracting the static density changes from the calculated dynamic density changes we find our genuine density changes within the ferrofluid. These were calculated to be 0.018953 g/cc, 0.030711 g/cc, and 0.033359 g/cc. The change in density was as high as 2.88%.

4.2 Significance of Results

It is significant that a change in density of the ferrofluid was observed during experimentation by subjecting the ferrofluid to the EM wave. The experiment indicated a maximum density change in the ferrofluid of 2.88% or 0.033359 g/cc; well within the range of non-olefin plastics. Based on experimentation results, higher voltages beyond the test parameters (ranging from 5.4V to 14.4V for the testing) may result in higher density changes as well. The ability to control the density of the ferrofluid makes it possible to sort plastics of varying densities. For example, if this system was being used to sort two plastics with different densities, the density of the ferrofluid could first be manipulated to be between the two plastic densities. This would result in one of the plastic types rising to the surface while the other one sinks towards the bottom. The plastic that has floated to the surface could then be collected. Once this is done the density of the ferrofluid could be made to be greater than that of the remaining plastic. This would have the effect of the remaining plastic rising to the surface where it could be collected.
Chapter 5

Conclusion

5.1 Conclusion

After conducting this experiment the research team discovered that it is possible to manipulate the internal pressures of ferrofluid using a predetermined electromagnetic pulse. After applying a low pass filter the research team was able to determine the resulting net change of pressure and specific gravity as displayed in Table 4.1. As displayed in Figures 4-1 through 4-3, when exposed to the pulse, the ferrofluid completely reorders and causes a decrease of specific gravity. The research team believes this to be a natural quality of colloidal liquids. Therefore the team has concluded that ferrofluid’s specific gravity can rapidly be changed via a magnetic pulse, while still preserving the temperature of the ferrofluid.

This novel method offers several advantages over existing methods for the sortation of plastic particles. This method is able to sort shredded plastic particles, whereas the most commonly used method of near infrared scanning is utilized for whole plastic containers. From a cost standpoint, the ferro-EM method requires significantly less equipment and space versus the most common method of using differential fluids.
and much less time. The differential fluid method requires several sequenced tanks containing fluids of different densities to cascade the plastic particles through and achieve sortation. This ferrofluid EM based method would only require one tank and less fixed equipment to move the particles through the system, achieving cost advantages.

This particular experiment presented some sources of error. Firstly, human error was a possible creation of error. Secondly, it is possible that error appeared from our computer/DAQ system. Lastly there is the possibility of the magnetic pulse affecting the measurement devices and disrupting the voltage signal. After concluding this experiment, static tests were taken to help determine whether electromagnetic waves corrupted signals. In the electromagnetic coil thermocouple, a major disruption was observed. The research team concluded that its extremely close proximity to the EM pulse may have led to its corruption. This was corrected by taking the temperature before/after the coil was active. As for the other two thermocouples, very little disruption was observable, both in dynamic and static tests. Finally, after conducting static tests the research team was able to determine a slight level of electromagnetic disruption in the pressure transducer. This has been quantified and has been used to confirm actual pressure changes.

This report serves as a proof of concept of the ferro-EM method of sorting shredded plastic. From this experiment, the research team will progress into stage two of this experiment. The research team intends to re-examine the core design and the frequency of the voltage to maximize and refine the magnetic pulse to produce an accurate change in the specific gravity of the ferrofluid. Future plans also include the design and creation of a larger scale test setup.
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http://www.epa.gov/osw/conserve/materials/plastics.htm


http://www.recyclingworkscampaign.org/federal-policy-recommendations/


