

Separation of Glass Spheres from Silver Coated Glass Spheres

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In past experiments on electric percolation, mixtures of small glass spheres and silver coated glass spheres have been created. To be able to reuse these spheres in further experiments an efficient method for separating the spheres is needed. This experiment explores the option of utilizing eddy current separation to separate the spheres. The possibility of scaling down an eddy current separator like those used in the processing of scrap metal seems promising but results are inconclusive at this point. A rotating magnetic drum creates a rapidly changing magnetic field that induces eddy currents in the thin silver coating. These eddy currents create a magnetic moment opposing the applied magnetic field that results in the particle being accelerated off the end of the separator where they can be collected separately from the glass spheres.

INTRODUCTION

In previous research on electrical percolation at The College of Wooster, mixtures of small silver coated glass spheres and non-coated glass spheres were created to measure the amount of current that flows through the mixture. There is currently no way of separating the spheres after the experiment and a solution to this problem is not immediately apparent. These spheres are approximately 1 mm in diameter so it is very hard and time consuming to separate them by hand. Also, coating these spheres with silver is rather costly so being able to separate and reuse them is valuable. It is not possible to separate the spheres by size since the silver coating is very thin, on the order of tens of microns [1]. Since the spheres are small, and since there are 400,000 of them, some sort of mechanical separator is desirable. A scaled down version of an eddy current separator appears to be the best way of separating the glass from the silver coated glass spheres.

EDDY CURRENT SEPARATOR BACKGROUND

Eddy current separators have been used for many years to separate metals from non-metals and ferrous metals from non-ferrous metals. This kind of separator is extensively used in the processing and recovery of scrap metals and recyclables. The separation technique is based on the fact that a conductive metal will try to resist being moved in a magnetic field. Magnetic damping works due to this

principle as well. This principle also works in reverse, so that if the magnetic field is changing, the conductive metal will try to resist this change resulting in a force on the metal. In eddy current separators, a rapidly changing magnetic field is created by quickly rotating a drum on which there are magnets alternating polarity as seen in Fig. 1 [2].

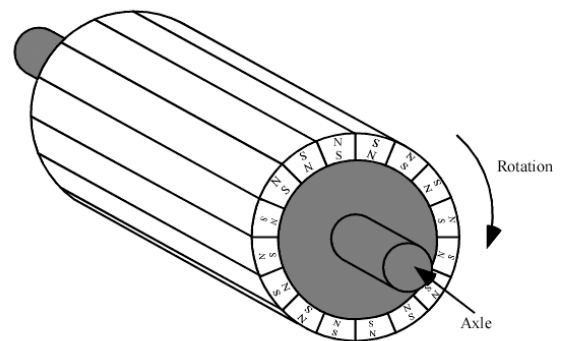


Fig. 1. Rotating drum used in eddy current separators. The magnets secured to the outside of the drum alternate polarity. One magnet will have the north pole facing out and the next will have the south pole facing out. As the drum spins it creates a rapidly changing magnetic field

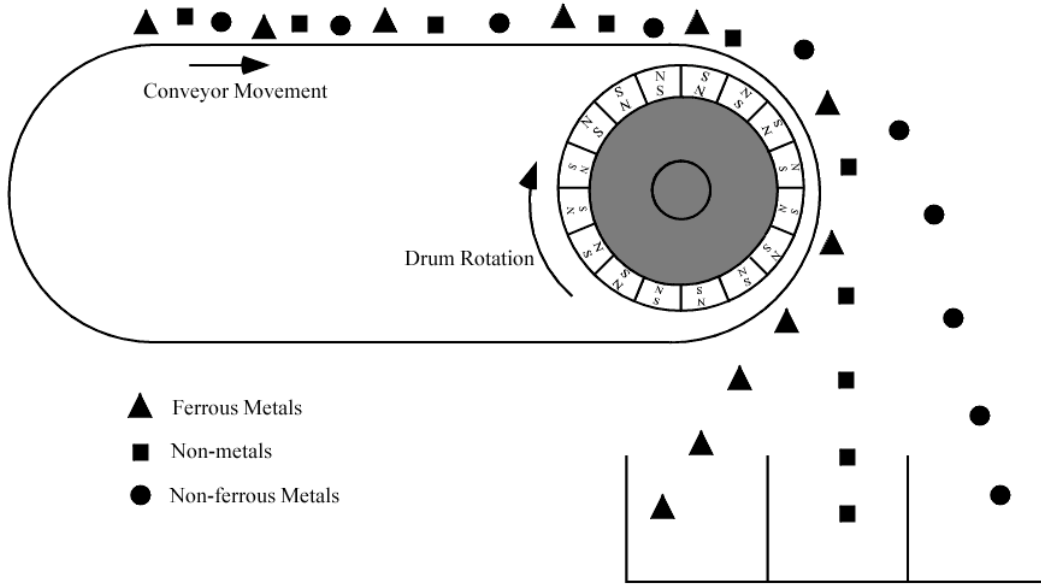


Fig. 2. Eddy current separator. As the conveyor brings the particles into the changing magnetic field three things can happen depending on the particle. Ferrous particles will be attracted to the drum and stay on the belt until the magnetic field weakens to the point where the particle falls. Non-metallic particles will not be affected by the magnetic field and will just fall off the end of the conveyor. Conductive non-ferrous particles are forced off the end of the conveyor. Three containers can be used to catch the three kinds of particles.

This rapidly changing magnetic field is what will supply the force to separate particles of different types. Generally, a conveyor carries the particles that are to be separated over the rotating drum as seen in Fig. 2. As the particles are brought into this area of changing magnetic field the electrons in metal experience the Lorentz force and begin to move. Within the metallic particles these swirling electrons create small currents called eddy currents that give the particle a dipole moment that opposes the change of the applied magnetic field. Depending on the rotation speed of the drum and the strength of the magnets, the force on the particle resulting from the dipole moment opposing the applied field can be enough to lift the particle off the conveyor and even throw it. The force on conductive non-ferrous particles allows eddy current separators to effectively separate particles into three categories: ferrous metals, non-metals, and non-ferrous metals. Ferrous particles will be attracted to the magnetic drum and stick to the conveyor until they are carried far enough from the drum that the attractive force of the ferrous particles to the magnets on the drum can no longer counteract the force of gravity and they will fall. Non-metal particles such as glass, plastic, or ceramic are not affected by the changing magnetic field and will fall normally when reaching the end of the conveyor. Non-ferrous metal particles experience eddy currents and are thrown from the conveyor,

which allows the three types of particles to be separated by placing three containers under the end of the conveyor where each type of particle will fall [2].

THEORY

The development of this theory follows that of Rem in his paper *A model for eddy current separation* [3]. As a particle enters the applied magnetic field $\vec{B}^a(\mathbf{r},t)$, it experiences a change in the size and direction of the field. This change is due to the translational and rotational movements of the particle. The fact that the drum is rotating also causes \vec{B}^a to be time and position dependent. The changing field as experienced by the particle can be defined as $\vec{\beta}^a(t)$, that is \vec{B}^a as experienced in the particle's frame of reference. To transform between the lab reference frame \vec{B}^a and the particle's reference frame $\vec{\beta}^a$ the transformation matrix $U(t)$ is used. Therefore

$$U(t) \cdot \vec{\beta}^a(t) = \vec{B}^a(\mathbf{r}(t),t). \quad (1)$$

By taking the derivative of both sides of Eq. 1 with respect to time one obtains

$$\frac{d}{dt} U \cdot \vec{\beta}^a + U \cdot \frac{d}{dt} \vec{\beta}^a = \frac{\partial}{\partial t} \vec{B}^a + \frac{\partial}{\partial r_i} \vec{B}^a \frac{dr_i}{dt}. \quad (2)$$

To attain an equation for the change in the magnetic field with respect to time, the first term of Eq. 2 must be moved to the right side of the equation. To simplify things even more the relation

$$\frac{d}{dt}(\mathbf{U} \cdot \vec{\beta}^a) = \frac{d}{dt} \vec{B}^a, \quad (3)$$

is used. Since this is in a rotating reference frame the time derivative of the applied field can be written in terms of the angular velocity Ω to become [4]

$$\frac{d}{dt} \vec{B}^a = \Omega \times \vec{B}^a. \quad (4)$$

After this simplification the result is

$$\mathbf{U} \cdot \frac{d}{dt} \vec{\beta}^a = \frac{\partial}{\partial t} \vec{B}^a + (\vec{u} \cdot \nabla) \vec{B}^a - \Omega \times \vec{B}^a, \quad (5)$$

which is an equation for the change in the magnetic field with respect to time where $\vec{u} = d/dt \vec{r}$ is the translation velocity and ∇ is the gradient operator.

The current density $\vec{j}(\vec{r}, t)$ is dependent on the position inside the particle \vec{r} and also time. This distribution of eddy currents inside of the particle increases linearly with the induced electric field $\vec{\epsilon}$ through

$$\vec{j} = \sigma \vec{\epsilon}, \quad (6)$$

where σ is the conductivity. To find the total force \vec{F} due to these eddy currents the Lorentz force is integrated over the volume of the particle

$$\vec{F} = \mathbf{U} \cdot \int_V \vec{j} \times \vec{B}^a d^3r. \quad (7)$$

The coordinate transform \mathbf{U} is used again to put this force into the reference frame of the lab. There is also a torque \vec{T} on the particle

$$\vec{T} = \mathbf{U} \cdot \int_V \vec{r} \times (\vec{j} \times \vec{B}^a) d^3r, \quad (8)$$

which is caused by the eddy currents within the sphere.

When the particles are adequately small there is little variation in the applied field within the particle, which allows \vec{F} and \vec{T} to be expressed in terms of the magnetic moment \vec{M} of the particle

$$\vec{M} = \frac{1}{2} \int_V \vec{r} \times \vec{j} d^3r. \quad (9)$$

By using the magnetic moment, Eq. 7 and Eq. 8 become

$$\vec{F} = \vec{M} \cdot \nabla \vec{B}^a, \quad (10)$$

and

$$\vec{T} = \vec{M} \times \vec{B}^a. \quad (11)$$

This means the problem of computing the force and torque rests in computing the magnetic moment of the particle which is not an easy task. The problem becomes even more complicated since the magnetic moment is dependent on time and must be related to the applied field which is also time dependent. Completing this computation is outside of the scope of this paper but others such as Rem [3] have done it.

EXPERIMENTAL TESTS

To initially test if eddy currents would be an acceptable method of separation I used 3 mm stainless steel and glass spheres. This was done because the 3 mm spheres were much easier to handle and also cost much less than the silver coated spheres. These larger spheres were used until I had a better idea of how the spheres would react to magnetic fields. The first test involved rolling the spheres through a stationary magnetic field hoping that the translational and rotational movement of the spheres through the magnetic field would create enough eddy currents to slow them. By creating a speed difference it was possible to separate the spheres by placing two containers under the bottom of the incline. The faster glass spheres fly farther off the ramp than the slower metallic spheres as shown in Fig. 3. By placing two containers at the bottom of the ramp where the two types of spheres fall, each container contains only one type of sphere. To keep the spheres rolling in a straight path on the ramp a plastic U shaped channel approximately 5 mm wide was placed on the ramp. Using the U channel allowed the spheres to be dropped into the channel at the top of the ramp without having to worry about giving them a transverse velocity. Three ceramic magnets each approximately 0.4 gauss were taped on the under side of the ramp to produce the magnetic field.

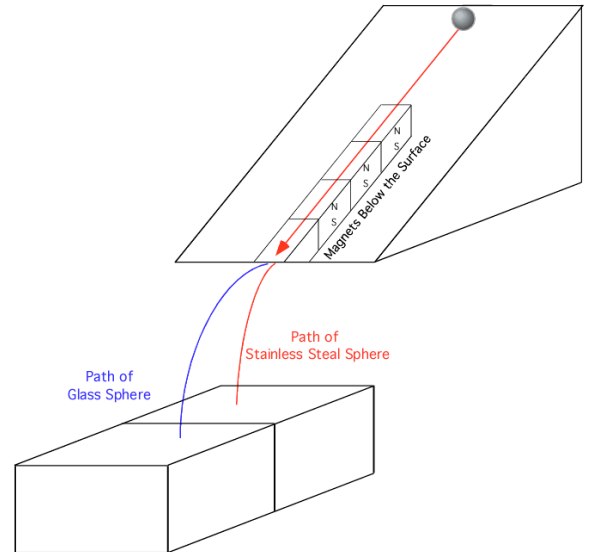


Fig. 3. Set up used with the 3 mm spheres. As the spheres roll down the incline over the magnets the stainless steel spheres slow down. Since the glass spheres have a greater velocity they travel farther off the ramp and land in the farther container. The slower stainless steel spheres fall off the ramp into the first container.

This set up worked well for the large spheres and I was able to separate them with a high degree of accuracy. However when I tried to separate the 1mm glass and silver coated glass spheres I was not able to effectively separate them. I found that since the spheres had such a small mass the slightest amount of static charge would cause them to stick to the plastic channel. Because of this I tested many materials that would not be affected by static charge to use as a channel including glass, aluminum, brass, and tin. However, there was still no noticeable difference in the landing position of the spheres in any of these cases even after doubling the amount of magnets under the ramp. The conclusion I reached from this is either the magnetic field was not strong enough, or the particles were not moving fast enough to create sufficient eddy currents in the silver coated spheres to slow them any noticeable amount. There is also the possibility that eddy currents were not the force slowing the 3 mm stainless steel spheres. Stainless steel is slightly attracted to magnets so as the spheres rolled down the incline the magnetic attraction between the magnet and the spheres may have been the reason the spheres were slowed. There is evidence that this was actually the case; if the angle of the incline was decreased so the spheres were rolling very slowly they would actually stop over the magnets. If eddy currents were the only force

involved here the sphere would not stop; just slow down. They would not stop because the eddy currents are induced due to the changing magnetic field. The magnetic field is changing because the sphere is moving, so as soon as the sphere would stop there would be no more eddy currents since there would no longer be a changing magnetic field. Without the eddy currents the sphere would have nothing holding it back and would start rolling down the incline again. This shows that there are more forces acting on the stainless steel sphere than just eddy currents since the stainless steel spheres did stop.

To increase the speed of the changing magnetic field I decided to construct a miniature version of an eddy current separator like those used in separating scrap metal and recyclables.

MINATURE SEPARATOR

The scaled down version of an eddy current separator that I constructed is shown in Fig. 4. The separator consists of a motor that rotates at approximately 1500 RPM and spins a piece of PVC pipe that has four rows of ceramic magnets screwed to it that alternate polarity orientation. Instead of using a conveyor to move the spheres over the rotating drum, a piece of polycarbonate was placed over top of the separator at a slight angle and the spheres were rolled down the incline.

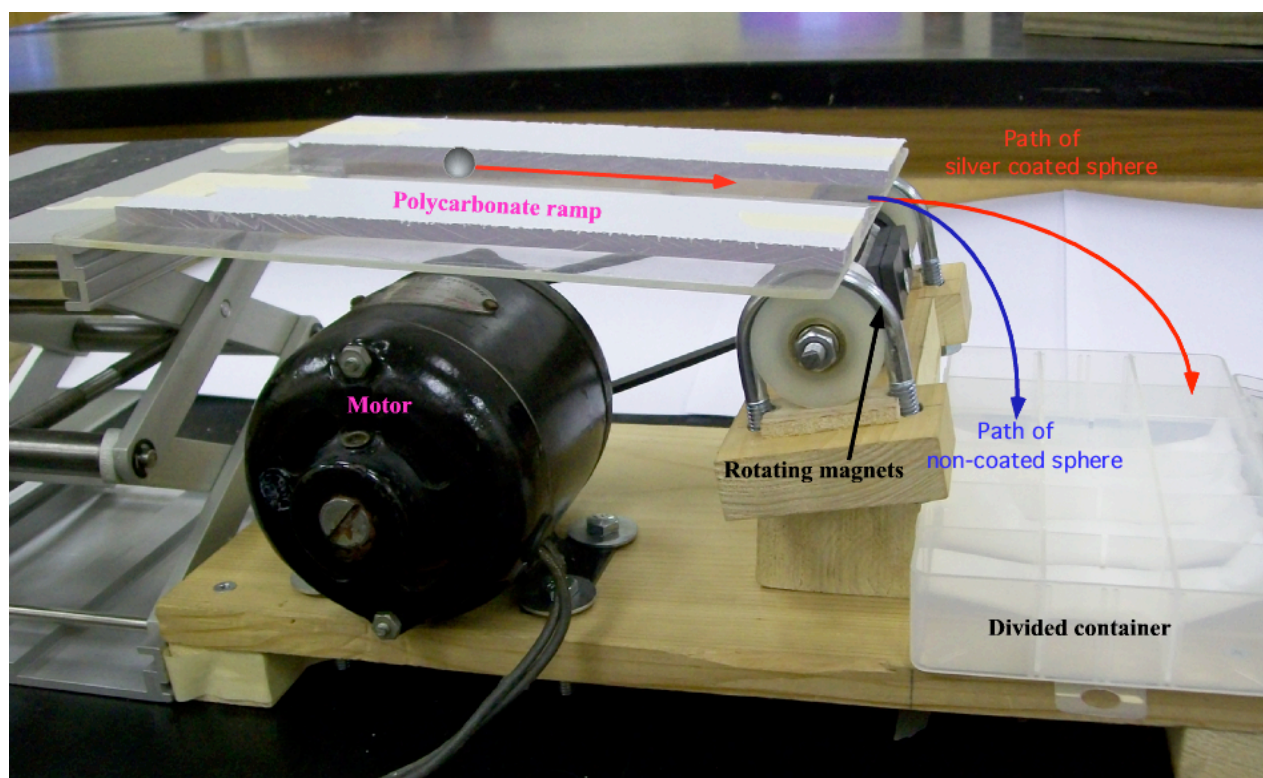


Fig. 4. Scaled down eddy current separator. The motor spins the magnet to create eddy currents in the silver spheres. The theoretical paths of the spheres are shown; the path of the glass spheres is shown in blue and the path of the silver coated spheres is shown here in red

The piece of polycarbonate was placed at an angle so the spheres would slowly roll down and over the rotating magnets. Two more pieces of polycarbonate were placed along the sides of the ramp to keep the spheres rolling straight. The polycarbonate ramp was placed so that the edge was just past the rotating magnets to allow the silver coated spheres to be thrown off the end as they accelerate due to the force of the eddy currents induced by the rotating magnets. Since the glass spheres are not affected by the magnetic field they would just fall normally while the silver spheres would be thrown farther from the end of the piece of polycarbonate because of their acceleration. A plastic container with divisions was placed at the bottom of the incline to catch the spheres after rolling off the polycarbonate.

After testing the separator there was no noticeable difference in the trajectory of the glass and silver coated glass spheres. At this point there seemed to be one possible reason for the separator not working the magnetic field was not strong enough to create adequate eddy currents. To test if the strength of the magnets I used were comparable to those used in other eddy current separators I cut up an aluminum can into small pieces to see if the miniature separator would accelerate them. The pieces of the can did not seem to be effected by the changing magnetic field. Since eddy current separators are used extensively in recycling to separate entire aluminum cans from other scrap, the miniature separator should at least be able to accelerate small pieces of a can. From this test it seems that stronger magnets would improve the function of the separator.

FUTURE WORK

One feature of the miniature separator that may be problematic is the polycarbonate ramp; the small spheres are not completely spherical which causes them to roll irregularly. The irregularities in rolling cause the spheres to have different speeds while rolling down the incline. For the eddy current separation technique to work correctly all particles must enter the magnetic field with the same speed. If the particles enter the magnetic field with different speeds it is not possible to tell the difference between a fast particle and a slow particle that has been accelerated by the magnetic field. It is possible that my separator was working to some extent but the differences in speeds of the spheres made it impossible to tell if some of the spheres were being accelerated. A possible solution to this is to use some sort of conveyor instead of rolling the spheres down an incline which would ensure that all the spheres enter the magnetic field with the same speed.

Two other areas of the miniature separator that could be improved are the in the number of pairs of magnets and the type of magnets used. Most eddy current separators generally have 6-10 pairs of magnets on their drums while my miniature separator only has 2 pairs. Fewer pairs of magnets effectively decreases the rate at which the magnetic field changes, reducing the strength of the eddy currents. Another difference between the miniature separator and most other separators is in the type of magnets used. The miniature separator uses ceramic magnets while almost every other separator uses neodymium magnets. Neodymium magnets are the most powerful magnets produced and are 18 times stronger than ceramic magnets [5]. Purchasing some neodymium magnets could help in both of these areas. Neodymium magnets can be purchased in almost any size and shape which means long skinny magnets could be purchased and glued onto the current piece of PVC pipe which would increase the number of pairs of magnets and in turn increase the rate at which the magnetic field changes.

CONCLUSION

There is currently no easy way to separate small glass spheres from silver coated glass spheres. To separate them all by hand would be difficult and very time consuming, which would make some sort of mechanical separator valuable. Eddy current separators are extensively used in scrap metal processing to separate non-metals from non-ferrous metals. A scaled down version of an eddy current separator seems ideal for this situation where the goal is to separate non-metallic glass spheres from glass spheres with a coating of non-ferrous silver. The current miniature separator does not actually separate the two types of spheres but there are several improvements that can be made to the design. By purchasing some small neodymium magnets the rate the magnetic field changes could be increased along with the field itself. New magnets should dramatically increase the performance of the miniature separator to the point where it could be used to reliably separate the spheres.

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