

Investigation of smart fluid properties in secondary schools

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Abstract

The electrorheological and magnetorheological fluids are complex liquids which can rearrange their structures in the presence of an electric or magnetic field. As the result of these structural changes the viscosity of these fluids increases up to several orders of magnitude. For these fluids— due to their controllable viscosity— there are many applications emerged in the modern engineering. In my work I will show methods, how to familiarize high school students with the physical causes of the behaviour of these advanced products of physics and materials sciences. In this paper, I will present a series of laboratory demonstrations as well as experimental investigations, which can easily be performed in the classroom. I will also show how smart fluids can be prepared given the kinds of equipment school teachers have at their disposal.

Keywords: electrorheological fluid, magnetorheological fluid, smart fluid

Introduction

If we look around in the world of technology, we will notice that surrounding objects we use in everyday life are becoming smarter. The TVs, refrigerators, washing machines, telephones, watches and even the houses are getting smarter, they include more sensors and actuators and possess more PC-like functions. This change does not only concern our devices, but also the materials used in them. Modern material science refers these as smart materials. It is difficult to give a good definition to these substances, because in many cases the type of use can make a material "smart". Perhaps the simplest way, we can say that a substance may be called intelligent, if they change their properties as the result of external effects beneficial for the user. Nowadays they may be either liquids or solids and it is also very likely that we do not have to wait much longer for the appearance of smart gaseous materials.

This article aims to provide recommendation for high school physics teachers, how they can familiarize their students with a special group of intelligent materials, the electro-(ER) and magnetorheological (MR) fluids, which was discovered just a few decades ago. I will show that the ER and MR effects and materials can be for our benefit not only in the future, but even in our present they may be around us, while most of the people are still not aware of their existence. It is important that future engineers are familiarizing themselves with these special materials in their high school years, because in the future large-scale spreads of their applications are expected.

The ER and MR effects

The electrorheological and magnetorheological fluids are complex liquids which can rearrange their structures in the presence of an electric or magnetic field. From here comes the name, since the science of rheology deals with the analysis of regularities between deformations and the effects what's causes them. In both types of fluids, the active particles get induced dipole moment by the external fields, which is why the induced

positive/magnetic north poles are trying to move near to the induced negative/magnetic south pole of a second particle. In the presence of the field at first the particles rearrange themselves into pairs, than chains, and later into columns. This process results in a drastic increase in viscosity, since the chains have to be broken by perpendicular shear forces in order to create deformations in the fluids [1].

The stress-strain behaviour of the Bingham viscoplastic model is often used to describe the behaviour of MR and ER fluids [2]. In this model, the plastic viscosity is defined as the slope of the measured shear stress versus shear strain rate data. Thus, for positive values of the shear rate $\dot{\gamma}$, the total stress is given by

$$\tau = \tau_{y(\text{field})} + \eta\dot{\gamma}$$

where $\tau_{y(\text{field})}$ is the yield stress induced by the magnetic or electric field and η is the viscosity of the fluid.

Electrorheological fluids

Electrorheological fluids can be prepared if particles with a dielectric permittivity of ϵ_p are dispersed in a liquid with an $\epsilon_f < \epsilon_p$ dielectric permittivity. If a viscosity of a liquid can be controlled by external electric field, it is called an electrorheological fluid.

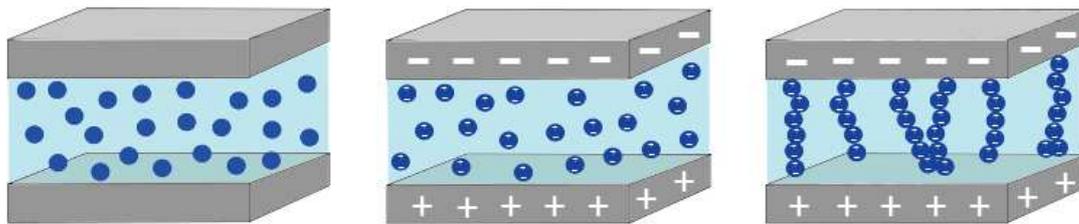


Figure 1. The chaining effect in an ER fluid in the presence of an external electric field

We can recognize a similar chaining phenomenon in a relatively frequently shown experiment in high schools, when we demonstrate the electric field lines with the help of a Van der Graaff generator by scattering ground grain into a layer of oil with the presence of high voltage (see Figure 2). The purpose of this experiment is generally to present the characteristics of the force field and field lines, therefore the explanation is sometimes omitted. Of course, the occurred chaining is also a consequence of the induced dipole moment of the particles.



Figure 2. Scattered ground grain on a layer of oil, in the presence of high voltage

How to make ER fluid at home?

We can create electrorheological fluids for ourselves by simply add starch into silicone or vegetable oil. The ratio of the ingredients should be roughly half and half. Tentatively we pour the prepared liquid from one container to another close to a charged glass or ebonite rod and if the fluid was prepared correctly, a water jet-like deflection can be experienced (see Figure 3). If the fluid is placed close to high voltage, we can experience an increase in its viscosity up to several orders of magnitude.



Figure 3. Homemade ER fluid jet close to a charged ebonite rod

In Figure 4 we can see electrodes which was put and then removed from a homemade ER liquid. In the first case, no voltage was connected to the electrodes, therefore the liquid flows out immediately from the metal plates. In the second case, a charged Van de Graaf generator was connected to one of the electrodes (the other electrode was connected to the ground), then the mixture did not flows out from the plates for a long time.

We can easily repeat this experiment for ourselves, but we need to know that the accumulated charge is discharging quickly through the fluid, since the generator is unable to maintain notable current. Therefore, the electrodes must be well insulated from the liquid. **If you decide to use high voltage power supply for this experiment, always proceed with caution!** We can use any metal plates as electrodes. Adjust the distance between them so that the generator do not discharge trough them. In addition, we should attach a nail to both of the electrodes which are slightly closer to each other than the distance of the electrodes, so we can avoid that the generator is discharged through the insulation.

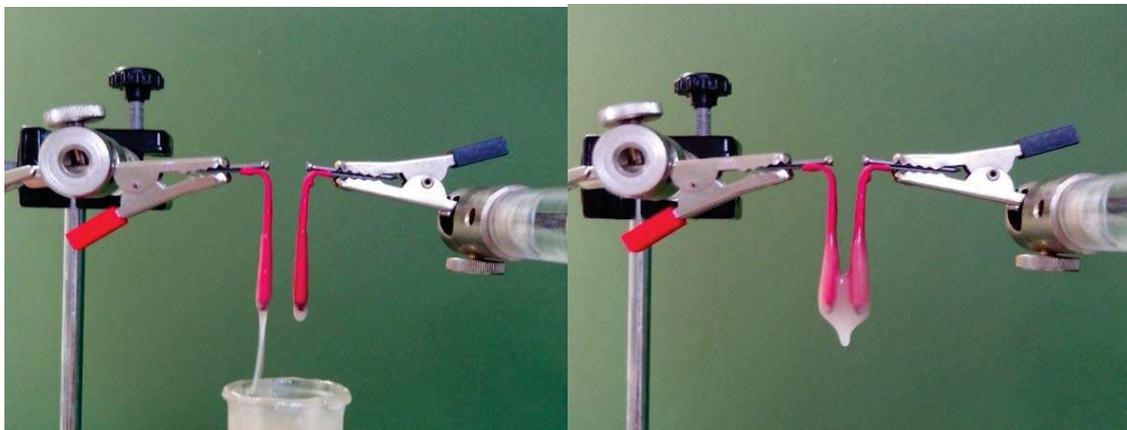


Figure 4. The behaviour of the ER fluid without and with high voltage

Measuring experiments with ER fluids

In high school, we can set up experiments to measure the field dependence of the viscosity of an ER fluid. We need to create an external electric field with a relatively controllable strength, and a homemade ER fluid. The external electric field can be simply created with a Van der Graaff generator. We can measure the time for a ball to sink in the liquid, or the time while the liquid flows out from a container with a hole in its bottom. As we change the strength of the external field, we can repeat the measurement and then we can plot the times in a graph. With this method, we can determine the critical field strength for chaining in our ER fluids.

Measuring viscosity with a falling ball

We can measure the viscosity of the fluid by using the principal of the Höppler viscosimeter by measuring the time required for a ball to fall under gravity through a sample-filled tube. The η (dynamic) viscosity is

$$\eta = \frac{2g(\rho_b - \rho_f)V}{9l} t$$

where g is the gravitational acceleration (m/s^2), ρ_b is the density of the ball (kg/m^3), ρ_f is the density of the fluid (kg/m^3), V is the volume of the ball (m^3), l is the length of the fall (m) and t is the measured time of the fall (s). At home, of course, we will be able to perform significantly less accurate measurements compared to the serial versions of the viscosimeter, but it provides a good opportunity for students to learn about the nature of viscosity. The measurement is carried out without external electric field, as well as its presence. From the maximum distance of the electrical breakdown the magnitude of the generator's voltage can be concluded ($\sim 20 \text{ kV/cm}$), then by multiplying the original distance of the electrodes, we can reduce the electric field strength (see Figure 5). Note that you can receive only highly imprecise values of the field strength with this method!

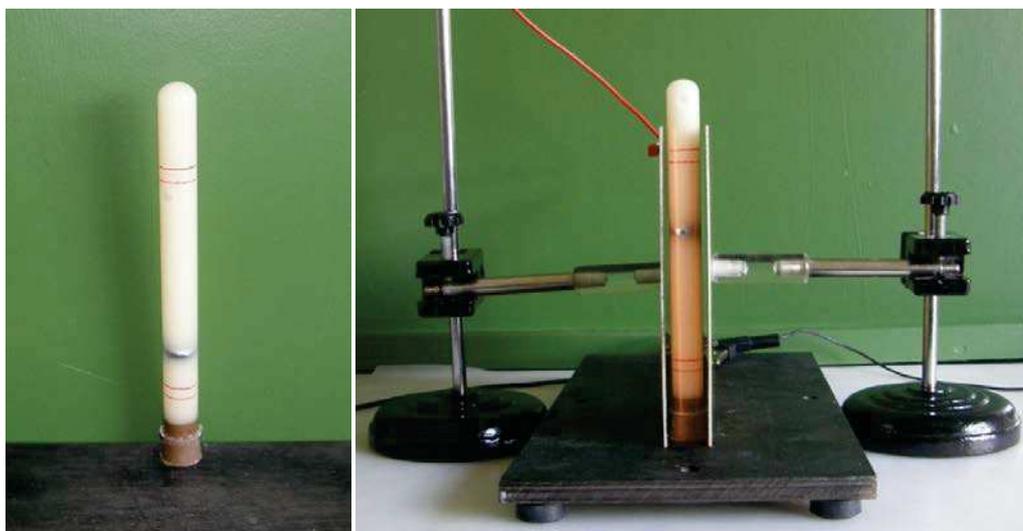


Figure 5. Measuring viscosity with a falling ball

Controlling the flow of an ER fluid with high voltage

If we let the ER fluid flow through a tube with electrodes on both sides, we can control the flow with applied high voltage to the electrodes (see Figure 6).

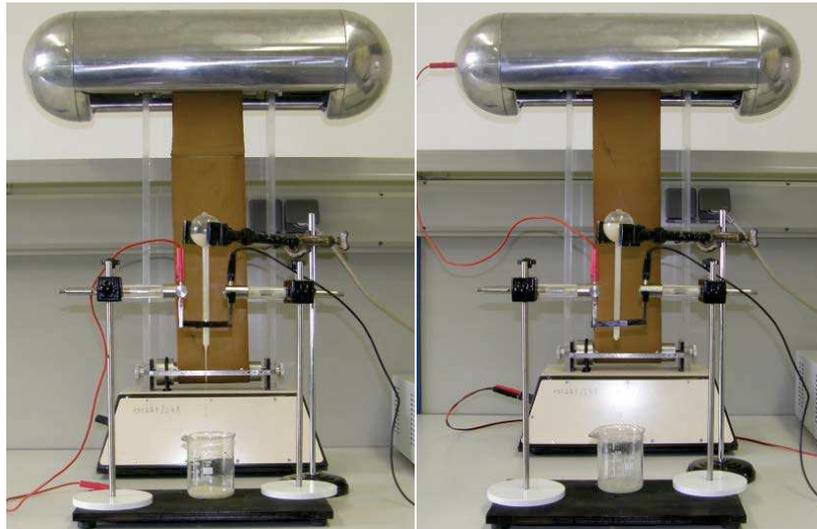


Figure 6. Controlled flow of an ER fluid by applied high voltage

Magnetorheological fluids

Magnetorheological fluids can be prepared by dispersing ferromagnetic particles with a magnetic permittivity of μ_p in a liquid with a $\mu_f < \mu_p$ magnetic permittivity. If the particles are so small, that there are only one magnetic domain in them, the magnetic fluid made from them is called a ferrofluid.

We can recognize a similar chaining phenomenon in a conventionally presented experiment, when we demonstrate the magnetic field lines by sprinkling iron filings on a sheet of paper and bringing a magnet up close to the underside of the paper, we can see that the filings line up along the lines of force (see Figure 7).

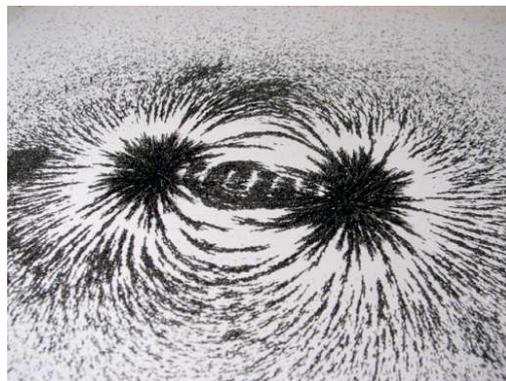


Figure 7. The iron filings line up along the lines of force

The chaining of magnetic particles can be presented by putting a layer of plastic balls and ball bearings into a magnetic field. For example, the balls can be placed between a picture frame backing, and glass, so they will not spread out and remain in the system in two dimensions (see Figure 8). When it is placed in a magnetic field, we should simulate the motion of the particles by vibrating the frame.

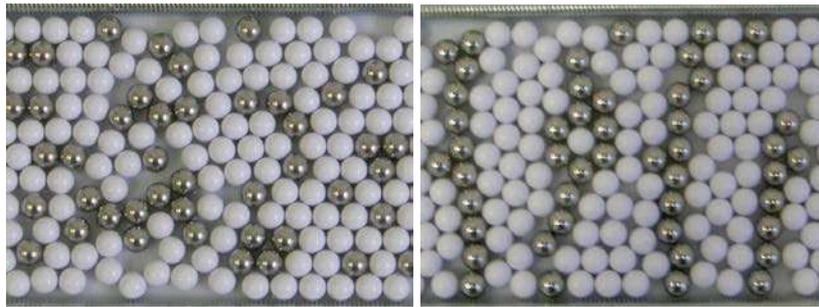


Figure 8. Bearing balls chaining in magnetic field

The MR fluids are almost solidified in the presence of an external magnetic field. In Figure 9 we can see an MR fluid placed in a strong magnetic field, if more MR fluid is dropped from above, a column-like structure can be built. When the magnetic field is turned off, the fluid does not keep shape, but almost immediately melt down (see Figure 9).



Figure 9. The behaviour on an MR fluid in an external magnetic field

If the used particle's size is so small, that it contains only one domain, we obtain so called ferrofluid. As the result of the small particle size the Brownian motion of these particles do not allows them to settle, this is why the ferrofluids are more stable than the MR fluids. The surface of the liquid draws a spiky shape in the presence of a magnetic field (see Figure 10).



Figure 10. The surface of a ferrofluid in the presence of an external magnetic field

How to make MR fluid at home?

At home, we can create only simple magnetic fluids by mixing silicone/vegetable oil, or water with fine iron or magnetite powder. To experience the MR effect, we need strong magnetic fields from neodymium- or electro magnets (see Figure 11).



Figure 11. Homemade MR fluid in increasingly powerful magnetic fields

The previously mentioned measurement experiments with ER fluids can also be performed with MR fluids, the needed magnetic field can be created by an electromagnet, therefore the field strength inside the coil can be calculated in the knowledge of the dimensions of the coil and the used current.

Magnetic elastomers

Magnetorheological elastomers (MRE) are viscoelastic solids whose mechanical properties are controllable by applied magnetic fields. They are prepared by curing a polymer containing dispersed magnetic particles in the presence or absence of a magnetic field.

How to make MRE-like materials at home?

We can create MRE-like materials at home (but not real MREs). We simply have to put fine iron or magnetite powder to commercially available gel powder before we pour hot water to it. After solidification of the gel it will show ferromagnetic properties, and its shape can be changed by an applied external magnetic fields (See Figure 12). In function of the applied field strength we can measure the occurred deformation.

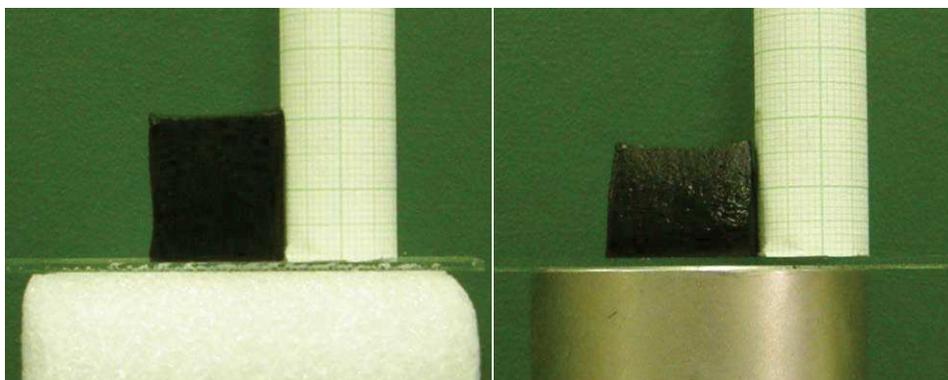


Figure 12. Homemade MRE-like material's reaction to strong (~ 300 mT) magnetic field

Applications

For these fluids – due to their controllable viscosity – there are many applications emerged in the modern engineering. The technical minded students should be familiarized with the tools based on the phenomena described so far, which can already be found in our environment.

Shock absorbers with a magnetorheological operating principle has been used in military vehicles (HMMWV) and since 2002 they are used in the civilian automotive industry too (Cadillac Seville STS, Audi TT and R8, Camaro ZL1, Ferrari 458 Italia). The hardness of these shock absorbers can be controlled within a few milliseconds.

ER and MR dampers are used in washing machines, speakers, stepping motors, air-conditioners, seats, and on a larger scale they are used in buildings and bridges in seismic systems (for example, in Japan's National Museum of Emerging Science and Innovation in Tokyo).

With the help of the controllable viscosity of the ER and MR fluids, wear-free brakes and clutches can be built, in which the rate of transmission can be controlled by changing the external field strength.

They are also used to create variable-shaped optical lenses, tactile displays, and used as printing inks as well as lubricants and sealants.

Water based, stabilized, biocompatible magnetic fluids are also used in the field of medical sciences as contrast agent for magnetic resonance imaging. In addition, for the delivery of paints and active substances with magnetic field, for separation of bio-components and for magnetic hyperthermic treatments.

Conclusions

In this paper, I have presented several laboratory demonstrations as well as experimental investigations, which can easily be performed in the classroom to familiarize students with smart materials. I have shown methods to prepare smart fluids at home, and I have shown that there is a wide range of application for these materials even in our present days.

Acknowledgments

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