Ferrofluid Properties and Applications

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Ferrofluids as nanomagnetic liquids have many unusual properties which are exploited in a variety of commercial applications. New families of ferrofluids, dry functionalized particles and solid superparamagnetic cores have contributed to the development of innovative industrial products. In this paper, fundamental properties of ferrofluids and nanoparticles are discussed, and the science and technology of some representative applications are presented.

Introduction
Ferrofluids have been in existence for about 50 years. During this period, a great deal of scientific understanding [1] and market applications has been achieved [2]. These are man-made materials in which magnetism is found in a liquid state with a high magnetic susceptibility. Ferrofluids are recognized as nano materials. The aim of this paper is to present physicochemical properties of current ferrofluids and how these properties form the basis of commercial applications and devices. Some applications such as seals and speakers have been around since the founding of the technology. No new replacement technologies have emerged. More recent applications are in the field of catalysis, recycling of scrap metal, superparamagnetic composites, and medical diagnosis and therapy.

Properties of a Ferrofluid
A ferrofluid is composed of three components: magnetic nano particles, dispersion medium (also called carrier liquid) and a dispersant or surface active agent. The fluid responds to an applied magnetic field as one homogeneous system. A typical ferrofluid is comprised, by volume, of about 5% solid component, 85% liquid and 10% surface active agent. The fluids are produced either by “scale down” or “scale up” approach. In the a “scale down” method, a ferrofluid is prepared by grinding large particles to nano size. “Scale up” methods are based on controlled nucleation and growth of nanoparticles and utilize such schemes as vacuum evaporation, microemulsions, chemical coprecipitation, organic precursors and sol-gel process [3].
The coprecipitation synthesis route is simple and economical and typically utilized at the industrial level. When viewed as a colloid, a ferrofluid represents a complex system in which several competing forces need to be balanced to ensure dispersion stability. These forces are: magnetic dipolar (attractive), Van der Waals (attractive), Brownian (random), steric (repulsive) and gravitational (attractive). The repulsive forces must outweigh attractive forces to avoid flocculation of the dispersed phase [4]. For a list of types of ferrofluids and physical properties, refer to Raj et.al [5].

**Ferrofluid Applications**
Ferrofluids are used in many industries. The applications are magnetic field dependent and can be grouped together by the nature of the applied field. Table 1 presents a list of applications and the type of field employed, e.g. DC, AC or Earth’s magnetic field. The majority of applications of the technology rely upon ferrofluid properties in a steady magnetic field which can range from 0.05 mT to 2T. Examples of these applications are seals, loudspeakers, dampers, electric motors, etc. However, the recent trend in applications, whether at commercial or exploratory levels, is to utilize relaxation time effects of particle moment in an AC field. Examples of such applications are: pathogen detection, hyperthermia and MRI contrast agent. Some representative applications from table 1 will be discussed along with the underlying physical principles.

**Rotary Feedthrough**
A rotary feedthrough is a mechanical device in which a ferrofluid is used as a sealant [6]. The seal was introduced in 1969 and is the most recognized and widely used product. It is commonly used in such high-tech industries as the semiconductor, laser, aerospace, solar, nuclear, etc. In all these applications clean environments are required for micro-level fabrication and processes. The feedthrough hermetically seals the chamber from the outside atmosphere and at the same time facilitates the manipulation and movement of parts in a vacuum. The
layout of a magnetic fluid seal is shown in Figure 1. It is cylindrical in shape and composed of a permanent magnet, pole pieces to channel the flux into an air gap, bearings to facilitate shaft rotation and a nonmagnetic housing. The shaft is marked with a teeth-like structure, creating regularly spaced intense and low magnetic field regions in the air gap. A ferrofluid captured in a high field region forms a liquid O-ring. There are several such O-rings. A typical O-ring contains about 3 µL of fluid, yet the seal has multiple years of life. The differential pressure capacity of each stage and total seal pressure capacity in the seal is given by Equation set 1.

((See attached equation 1))

Total pressure capacity of all stages is the sum of all individual stages:

((See attached equation 2))

Where n= number of stages, (µ0H) = magnetic field in the gap, (µ0M) = magnetization of ferrofluid
As an example, an application of the seal in the solar industry is described. The efficiency of a monocrystalline silicon cell is about 20%. The efficiency can be increased by about 5% by coating the cell with a thin film of a material such as ZnO, SiN, TiO2, etc. Chemical vapor deposition processes are commonly used for this purpose. The material of interest is vaporized under high vacuum and deposited on the cell surface, Figure 2. Trays of solar cells are transported on rollers through the chamber in a continuous manner. Several ferrofluid seals, driven by motors, provide rotary motion to the rollers and at the same time ensure contamination free environments in the process chamber.

**Diesel Particulate Trap Regeneration**

A complex mixture of gaseous and particulate matter is produced during the combustion of fuel in engines of heavy vehicles, Figure 3. The exhaust products are hazardous to the environment and health. A trap made of a high temperature material such as ceramic prevents the carbonaceous matter from entering the atmosphere, thus meeting the federal and local emission control standards. Over time the filter gets clogged with particles, typically less than 2.5µm. This obstruction leads to a back pressure of gases and a decline in engine performance. The trap thus needs to be cleaned or replaced periodically. It is possible to regenerate or self clean the trap by heating it to a temperature of about 600°C to burn off the soot. This is accomplished by increasing the temperature of exhaust gases, mixing it with fuel and using the trap as a second combustion chamber. A ferrofluid provides a more convenient way to regenerate the trap. The particles in the ferrofluid behave as a catalyst to promote combustion at a lower temperature, around 300°C. A low viscosity ferrofluid is mixed with diesel fuel, and upon
combustion in the engine compartment, produces iron containing compounds which are as usual trapped in the filter. The diesel exhaust can easily reach a temperature of 300oC and the trap is continuously regenerated, burning soot into ash during vehicle operation. Only environmentally friendly gases and iron oxide particles exit the tail pipe.

Conclusion
The nano-behavior of ferrofluids has led to the creation of an array of new applications and products in many industrial sectors. Fundamental properties of ferrofluids and nano particles were discussed along with the technical basis of devices. New ferrofluid developments leading to an increase in magnetization, electrical and thermal properties promise to further extend the frontiers of science and technology of these unusual materials.

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