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Technical note

Collection of airborne particles by a high-gradient permanent magnetic method ☆

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ABSTRACT

We report on the use of magnetic force in collection of airborne particles by a high-gradient permanent magnetic separation (HGPMS) device. Three aerosol particles of different magnetic susceptibility (NaCl, CuO, and Fe_3O_4) were generated in the electrical mobility size range of 10–200 nm and were used to study HGPMS collection. One HGPMS matrix element, made of stainless steel wool, was used in the device configuration. Three flow rates were selected to simulate the environmental wind speeds of interest to the study. Magnetic force was found to exhibit an insignificant effect on the separation of NaCl particles, even in the HGPMS configuration. Diffusion was a major mechanism in the removal of the diamagnetic particles; however, diffusion is insignificant under the influence of a high-gradient magnetic field for paramagnetic or ferromagnetic particles. The HGPMS showed high-performance collection (> 99%) of paramagnetic CuO and ferromagnetic Fe_3O_4 particles for particle sizes greater than or equal to 60 nm. As the wind speed increases, the influence of the magnetic force weakens, and the capability to remove particles from the gas stream diminishes. The results suggest that the HGPMS principle could be explored for development of an advanced miniaturized passive aerosol collector.

1. Introduction

Human exposure to particulate pollutants below 10 μm (PM_{10}), particularly those below 0.1 μm ($PM_{0.1}$), has been strongly associated with adverse health effects due to their ability to be inhaled deeply into the respiratory system (Pope, 1999; Pope et al., 2004). A large number of particle collectors are commercially available for monitoring ambient air quality, worker health and safety, process manufacturing, and so forth. The US Environmental Protection Agency has established an extensive network of samplers that routinely collect ambient particles for monitoring air quality and compliance to the National Ambient Air Quality Standards (http://www.epa.gov/air/criteria.html). Personal particulate monitors equipped

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with small pumps have also been commonly used by industrial hygienists for exposure measurement. These collectors require air sampling driven by a vacuum pump. Active samplers can be effective and less dependent on wind, but the downsides are that they are bulky, costly, noisy, and difficult to scale. Sampling by a vacuum pump is also known to alter the particle state (e.g., water and volatile components can be lost), leading to biased data. In deployment, the lack of a reliable power source may compromise the mission. For example, use of a sampling pump that draws power from an aircraft is prohibited (Guan et al., 2014).

Magnetic separation is a physical process that exploits the differences in the magnetic susceptibility of materials. Most of the rare earth oxides and actinide compounds are paramagnetic. Collection and concentration of actinides from air, water, or soil can be important for source identification in environmental monitoring (Hu et al., 2007; Qian et al., 2011; Shu et al., 2001). Because actinide compounds are paramagnetic, as shown in Fig. 1, magnetic properties have been used as an indicator of heavy metal contamination (Qian et al., 2011; Yang et al., 2010). Magnet-based techniques have also been developed for industrial applications. For example, a high-gradient magnetic separation (HGMS) technique based on electromagnets has been used in the kaolin clay industry to remove iron-stained anatase (titanium dioxide) particles with processing rates as high as 60 t/h. Removal of the iron-stained anatase whitens or brightens the clay, increasing its value. The separation technique has been applied for soil decontamination. Plutonium and uranium were extracted from contaminated soil with efficiencies of 60–90% (Avens et al., 1996; Padmanabhan & Sreenivas, 2011; Worl et al., 2001). These studies successfully demonstrated the feasibility of using HGMS to extract magnetic particulate components from water and soil. However, the quantity of experimental data is very limited for the capture of aerosol particles by HGMS.

Collection of aerosol particles by HGMS relies on the attraction force resulting from imposing a magnetic field against drag and gravitational forces. Zarutskaya & Shapiro (2000) showed by computational means that the capture of particles as small as 100 nm by a magnetic filter is enhanced as the superficial velocity is reduced. Li (2010) showed the effectiveness of a high-gradient electromagnetic filter based on a traditional diffusion-screen battery design for aerosol collection of iron oxide particles ranging in size between 100 and 300 nm. The collection efficiency for iron oxide (γ-Fe_2O_3) particles was in the range of 40–90% for particles in the size range of 100–250 nm under the wind speed conditions from 6 to 22 cm/s. Higher wind speed led to a lower efficiency of collection. When the electromagnetic field strength was increased from 20 to 40 kA/m, the collection efficiency improved from 60% at high speed to close to 99% at low speed. In terms of the use of permanent magnets, Hsiao et al. (2013) reported the design of a passive aerosol collector for personal monitoring based on an array of 186 small magnets for an aerosol man-in-simulant test application. There were no magnetic matrix element in their design to create a high magnetic gradient, but alternating the N-S arrangement of the magnets enhanced the collection within the turbulent boundary layer in the sampler. Thus they were able to show enhanced collection efficiency of iron oxide particles in the range of 95–300 nm by magnetic means in wind speeds ranging from 48 to 117 cm/s.

The advances in technology for manufacturing powerful permanent magnets have made it possible to consider building an HGMS collector for aerosol particles based on the magnets. The objective of this study is to extend our understandings of magnetic separation of aerosol particles by exploring the use of permanent magnets in a high-gradient permanent magnetic system (HGPMS) for removal of particles smaller than 200 nm in low wind speed conditions.

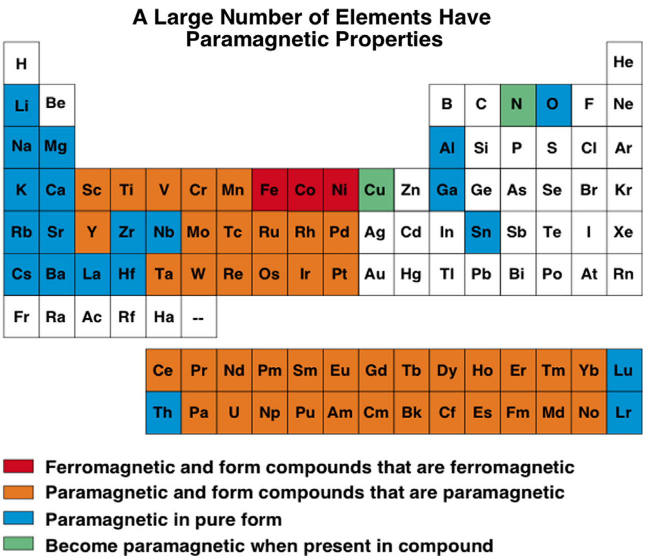

Fig. 1. Elements that have paramagnetic properties.