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Falling velocity magnetometry of ferromagnetic microparticles

Hitoshi Watarai *, Rong Fan, Jing Yang Liu, James Djauhari

Institute for NanoScience Design, Osaka University, Toyonaka, Osaka 560-8531, Japan

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ABSTRACT

A simple magnetometry of single ferromagnetic microparticles, which measures the falling velocity of a particle under the influence of magnetic Faraday force in air or liquid and characterizes the magnetic susceptibility of the particle, was constructed. Magnetic field gradient was applied to the falling particles and the velocity change of the falling particles was analysed taking into account the working forces to the particle. The feasibility of the present method was demonstrated by evaluating the magnetic susceptibility of ferromagnetic particles of cobalt, nickel and magnetic toner particles.

1. Introduction

Magnetophoresis is the phenomenon that a particle is migrated by the magnetic Faraday force under the magnetic field gradient. Magnetophoresis was proposed as a new principle for magnetometric measurements and continuous separation of particles in liquids, in which the migration velocity is proportional to the difference in the magnetic susceptibility between the particle and the medium [1–8]. It was applied not only to paramagnetic particles but also to diamagnetic particles such as polystyrene particles and blood cells [2]. Furthermore, the magnetophoretic velocity of a particle was used for the determination of the magnetic susceptibility of single crystals [6], oil droplets [4] and magnetic beads [5] in liquid. Especially, the group of Zborowski and Chalmers developed an electromagnet cell tracking velocimetry (CTV) for the precise measurement of magnetization and size distribution of micro-particles in liquid media [5]. However, as for the magnetophoresis in air, only a few studies were reported [9,10]. In particular, ferromagnetic particles in air have not been studied as the subject of the magnetophoretic velocimetry. Recently, various types of functional ferromagnetic particles such as magnetic ink and magnetic toner are commercially produced [10–13]. Today, modern instruments such as a superconducting quantum interference device (SQUID) and a vibrating sample magnetometer (VSM) are widely used to measure the magnetic susceptibility with high sensitivity. However, these techniques require a substantial cost and space for the installation. In the present study, we have constructed a simple and less expensive method, called falling velocity magnetometry, to evaluate the magnetic susceptibility of a single particle from the measurement of falling velocity under the influence of magnetic field gradient generated by a pair of permanent magnets. The feasibility of the present method was demonstrated by the measurements of magnetic susceptibilities of ferromagnetic metal microparticles and toner particles. For the metal particles, the measurements in liquid media were also carried out. Finally, the advantages and the limitation of the present method were discussed in comparison with the results obtained for the bulk samples by VSM.

2. Experimental

2.1. Materials

The metal particle samples of cobalt (1.46 ± 0.36 μm in diameter) and nickel (3.27 ± 1.20 μm) were purchased from Wako Pure Chemical Industries, Ltd. (Japan). The magnetic black toner samples A (5.68 ± 2.71 μm) and B (3.60 ± 2.29 μm), which are different in magnetic property, were donated from a manufacturer (Tomoegawa Co., Ltd., Japan). The size of the particles was measured from the images observed by a microscope (TE2000-U, Nikkon, Japan) with a CCD camera (Point Gray, FL3-U3, Edmond optics, USA).

2.2. Falling velocity magnetometry

A simple falling velocity magnetometry system was built as shown in Fig. 1(A). A 15 cm long and 15 mm inner diameter glass test tube was used as a falling tube, which is enough long to mea-

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* Corresponding author.
E-mail address: watarai@chem.sci.osaka-u.ac.jp (H. Watarai).

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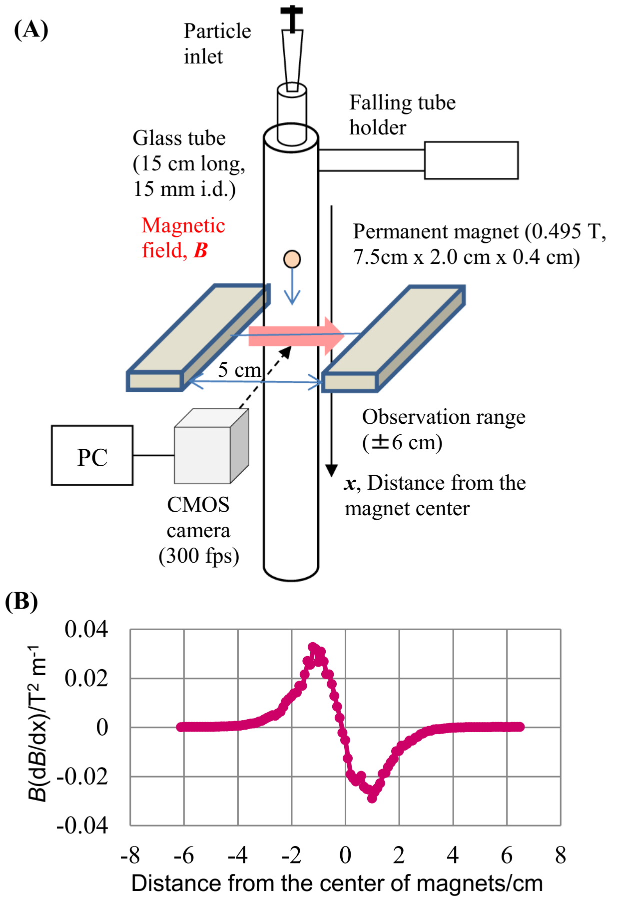

Fig. 1. (A) Set up of the measurement system to observe magnetic field effect on the falling velocities of particles, (B) Plots of the magnetic intensity, $B(dB/dx)$ against the vertical x-axis.

sure the velocity of falling particles under the influence of vertical Faraday magnetic force without any undesirable air flow. Particles were fed from the top of the falling tube indicated as a particle inlet in Fig. 1(A), which was made by a disposable tip of Eppendorf pipette (2–200 μL), set in a PTFE holder. By moving a copper wire inserted to the tip, particles were fallen from the hole of the tip. The magnetic field was applied horizontally by a pair of permanent magnets (0.495 T, 7.5 cm long × 2.0 cm width × 0.4 cm thickness), which was set with 5 cm distance at the middle height position of the tube (Fig. 1(A)). To decrease a leakage of magnetic field and to apply the magnetic field effectively to the tube, the magnets and the tube were covered by iron plates so as to make a magnetic circuit.

Falling particles were observed in the range of ±6 cm from the middle point of the tube, which was defined as the origin, by a CMOS camera (CASIO EX ZR1000) with a rate of 300 frames per second, and then the video images were analyzed to obtain the velocity and the acceleration with the help of Adobe Premiere Elements 11 and Image J. The magnetic flux density, B, along the vertical axis (x-axis) through the origin, which was defined at the center of the magnets, was measured by a Gauss meter (F. W. Bell, 5180, USA) as a function of the vertical distance from the origin. The value of B showed the maximum of 30.4 mT at the origin and was below 0.5 mT at the position of ±6 cm as shown in Fig. 1(B).

The magnetization of cobalt and nickel particles as well as magnetic toner was measured by a vibrating sample magnetometer (VSM) (PV-M20-5, Toei Scientific Industrial Co., Ltd, Japan) in the range of magnetic field of −20 to 20 kOe with a rate of 0.076 kOe/s.

2.3. Analysis of falling velocity

The forces working on a falling spherical particle in a magnetic field gradient are the gravity force, F_g, the viscous (or friction) force, F_f, the buoyancy, F_b, and the magnetic Faraday force including the magnetic buoyancy, F_m, which are represented respectively by,

$$F_g = mg \tag{1}$$

$$F_f = 6\pi\eta r v \tag{2}$$

$$F_b = m\frac{\rho_m}{\rho_p}g \tag{3}$$

$$F_m = \frac{(\chi_p - \chi_m)}{\mu_0}\frac{m}{\rho_p}B\frac{dB}{dx} \tag{4}$$

where m is the mass of a particle, g the acceleration of gravity, η the viscosity of a medium, r the radius of the spherical particle, v the falling velocity at the position x, ρ_p and ρ_m the densities of the particle and the medium, respectively, χ_p and χ_m the volume magnetic susceptibilities of the particle and the medium, respectively, μ_0 the vacuum permeability, B the magnetic flux density at the position x. For the particle falling downward on the x-axis, the forces of F_f and F_b are always working upward to the particle and F_g is downward, producing the observable acceleration. As for F_m, it depends on the position, under or below the magnet center ($x = 0$), due to the sign of $B(dB/dx)$. When a paramagnetic or ferromagnetic particle is falling above the magnet center, the force of F_m will work downward. On the other hand, when the particle is positioned below the magnet center, the force will work upward. Finally, these forces determine the acceleration, a, of the particle,

$$F_m + F_g - F_f - F_b = ma. \tag{5}$$

However, some difference in the analysis will be found in the media of air and liquid. In the case of air, the density and the volume magnetic susceptibility are much smaller than a liquid and a particle, then these can be neglected as $\rho_m = 0$ and $\chi_m = 0$. Therefore, the equations of

$$F_m + F_g - F_f = ma \tag{6}$$

$$F_m = \frac{\chi_g}{\mu_0}mB\frac{dB}{dx} \tag{7}$$

are derived, where χ_g is the mass magnetic susceptibility of the particle, $\chi_g = \chi_p/\rho_p$. In addition, the terminal velocity of the particle, v_∞, in the negligible magnetic field, where the acceleration will be zero, is represented by,

$$v_\infty = \frac{mg}{6\pi\eta r} = \tau g \tag{8}$$

$$\tau = \frac{m}{6\pi\eta r} = \frac{v_\infty}{g} \tag{9}$$

where τ is the relaxation time of the particle. From the above equations, the next equation,

$$g\left(\frac{v}{v_\infty} - 1\right) + a = \frac{\chi_g}{\mu_0}B\left(\frac{dB}{dx}\right) \tag{10}$$

is obtained. The left hand side of the equation can be obtained experimentally and it can be plotted against $B(dB/dx)$, giving a