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High-magnetic-field electromagnetophoresis of micro-particles in a capillary flow system

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Abstract

The electromagnetophoretic migration of micro-particles in a capillary flow system was demonstrated using a homogeneous magnetic field applied at right angles to an electric current. We utilized a high-magnetic-field of 10 T for observing this phenomenon. When the direction of the electric current was alternatively changed, polystyrene latex particles in a flowing aqueous medium migrated zigzag affected by a Lorentz force exerted on the medium. Carbon particles also migrated in the same manner with polystyrene particles. Further, we tried the electromagnetophoretic migration of biological particles, such as yeasts and human red blood cells. The migration velocity component perpendicular to the flow was proportional to both the electric current and the magnetic flux density. These results proved that the dominant force of the zigzag migration was an electromagnetophoretic buoyancy generated in the flowing medium. Moreover, it was found that the force exerted on the particles in the magnetic field of 10 T was sufficient for the desorption of particles adsorbed on the capillary wall.

Keywords: Electromagnetophoresis; Magnetic separation; Surface conductivity; Instrumentation; Polystyrene; Carbon

1. Introduction

Electrophoresis and sedimentation are currently the most popular migration methods of biomolecules and cell composites, which are utilizing an electric field and a gravitational field, respectively [1,2]. Recently, some separation methods using a magnetic field were also made practical. In these methods, magnetically susceptible particles or Fe_2O_3 adsorbed particles were separated by an inhomogeneous magnetic field [3]. Although there are some other external fields that might be utilized for migration analyses of microparticles, they have so far hardly been investigated. In our laboratory, some of the alternative external fields were investigated for the development of new migration analysis. A nonuniform electric field was utilized in the dielectrophoresis [4], a scattering force of laser radiation beam was employed in the laser-photoporesis [5], and an inhomogeneous magnetic field was used in magnetophoresis [6,7]. We focus here on an electromagnetic force which is produced by a homogeneous electric field and a homogeneous magnetic field, in order to invent a new principle for the migration analysis of microparticles in solution. The flow controlling of electrolyte solutions using the electromagnetic force, such as magnetohydrodynamics (MHD) effect, have been studied [8,9], however, particle analysis using this force have been investigated scarcely.

The general concept of electromagnetophoresis (EMP) is an application of Lorentz force to the migration analysis. When we apply an electric current through a conductive fluid including particles in a homogeneous magnetic field perpendicular to the current, the force is exerted on both the fluid and the particles. If the force exerted on the fluid is equal to the one working upon the particles, no migration will occur. However, if the two forces are different, migration of the particles will be caused.

A theory of electromagnetophoresis was proposed for the first time by Kolin in 1953, and the force exerted on macroscopic beads was experimentally demonstrated [10]. Recently, the electromagnetophoretic velocities of microscopic particles, such as polystyrene latex spheres, were investigated in our laboratory. Measurements in our laboratory have been performed in a closed microcell under a magnetic field less than 0.2 T generated by permanent Nd–Fe–B magnets. It was confirmed from this study that the migration velocity of particles was proportional to the current, the magnetic field and the second power of the particles' radius [11].

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In the present study, we investigated the electromagnetophoresis of micrometer-sized particles in a flow system, which was widely adapted in high-throughput separation systems. Furthermore, we applied a superconducting magnet, which could allow us to use a high-magnetic-field up to 10 T. Therefore, we could observe the migration velocity induced by the larger force than that by permanent magnets.

In this paper, we describe the experimental observation of the electromagnetophoretic behavior of microscopic particles, such as polystyrene latex and carbon, in a capillary flow system using a high-magnetic-field and discuss the dependence of the electromagnetophoretic velocities on the magnetic field, the electric current, the particle size and the conductivity of the particle. Further, we tried to measure the desorption force of the particles adsorbed on the capillary wall by applying electromagnetic buoyancy.

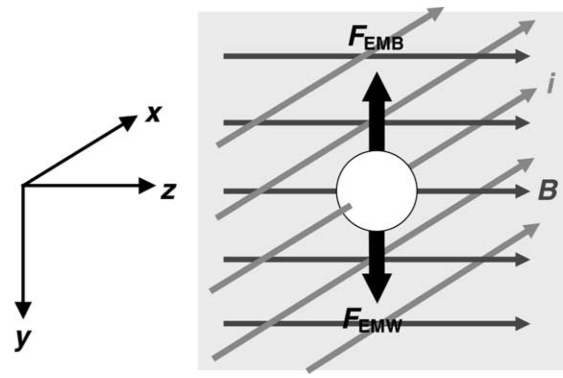

Fig. 1. Schematic drawing of the electromagnetic weight, F_{EMW}, and electromagnetic buoyancy, F_{EMB}, exerted on a particle. They are perpendicular to a homogeneous magnetic field (*B*) and to an electric current (*i*). The magnetic field is maintained at right angles to the current.

2. Material and methods

2.1. Principal of electromagnetophoresis

When the current of j ($A\,m^{-2}$) passes through a conductor of volume V (m^3) in a magnetic field, the conductor invariably experiences a force, the Lorentz force. If the current is perpendicular to the magnetic field, this force can be expressed as:

$$F = \mu_0 \mu H j V \quad (1)$$

where μ_0 is the vacuum magnetic permeability ($N\,s^2\,C^{-2}$), μ the magnetic permeability of the conductor and H the magnetic field strength ($A\,m^{-1}$). The direction of the force is perpendicular to both the current and the magnetic field.

The same force can be generated even when the conductor is the fluid. As the current passes through the conductive fluid enclosed in a cell under a magnetic field, all of the fluid experiences the force. Although the fluid is stationary while passing the current, the pressure in the fluid generated by the Lorentz force depends on the position and thus a pressure gradient is produced. This phenomenon plays a key role in our experiment.

One can imagine a homogeneous electric current and a homogeneous magnetic field, which are applied to a cell at right angles to each other. Fig. 1 shows a schematic drawing of this situation and forces exerted on a particle in a fluid in the cell. The densities of the particle and the fluid were kept almost equal in our experiment, so that any influence of the gravitational force was neglected. As we applied a current through the enclosed conductive fluid in the homogeneous magnetic field, they migrated to the direction perpendicular to the current and the magnetic field. According to Kolin, whether the particles migrate upward or downward (Fig. 1) depends on the difference between the fluid conductivity and the particle conductivity. The two forces working on a particle (Fig. 1) are called the electromagnetic weight (EMW) and the electromagnetic buoyancy (EMB). F_{EMW} is a force working on a particle, itself. On the other hand, the direction of F_{EMB} is opposite to F_{EMW}, and the strength of F_{EMB} is equivalent to the force working on the fluid whose volume is equal to that of the particle.

The net force exerted on a particle in a closed cell which has an inner section of S (m^2) given by Kolin is F_{EMW} added by $F_{EMB,}$ as shown in the following equation:

$$F_{EMP} = F_{EMW} + F_{EMB} = 2BV\left(\frac{\sigma_p - \sigma_f}{2\sigma_f + \sigma_p}\right)\frac{i}{S} \quad (2)$$

where B is the magnetic flux density ($N\,A^{-1}\,m^{-1}$), σ_p is the apparent electric conductivity ($S\,m^{-1}$) of the particle and σ_f is the electric conductivity ($S\,m^{-1}$) of the medium, and i the current (A).

Acceleration and mass of the particles are so small in our system that the particle migrate with a constant velocity, v, keeping balance between the electromagnetophoretic force, F_{EMP}, and the viscous or frictional force, F_v, which is expressed by Stokes' law:

$$F_v = 6\pi\eta r v C_W \quad (3)$$

where η is the fluid viscosity (Pa s), r the radius of the spherical particle (m), C_W is the viscous drag coefficient due to the surface of the cell wall.

From Eqs. (2) and (3), we can obtain the migration velocity v of a spherical particle as:

$$v = \frac{4}{9}\left(\frac{\sigma_p - \sigma_f}{2\sigma_f + \sigma_p}\right)\frac{iBr^2}{S\eta C_W} \quad (4)$$

Eq. (4) indicates that the electromagnetophoretic velocity will be proportional to i, B and r^2.

2.2. Materials

The particles used in the experiments were polystyrene latex particles and carbon particles. Polystyrene latex particles were purchased from Funakoshi (Tokyo, Japan), and carbon particles were purchased from Nippon Carbon (Tokyo,

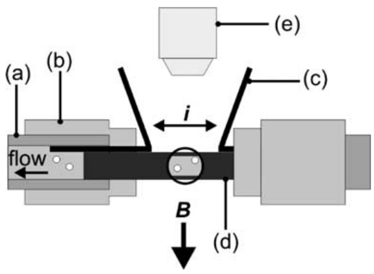

Fig. 2. Diagram of the cell: (a) PTFE tube, (b) heat-shrink tube, (c) Ag|AgCl electrodes, (d) fused-silica capillary, and (e) objective. PTFE tube was connected to a syringe pump. The observation part was the center of the capillary. The homogeneous magnetic field (*B*) is applied to the direction of the gravity and the direction of the current (*i*) can be alternatively changed.

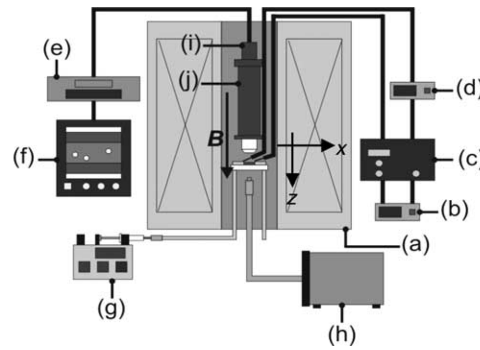

Fig. 3. Experimental setup for the observation of electromagnetophoresis: (a) superconducting magnet, (b) voltmeter, (c) current source, (d) ammeter, (e) video recorder, (f) monitor, (g) syringe pump, (h) light source, (i) CCD camera, and (j) optical microscope.

Japan). The diameters of polystyrene latex particles were 6 ($5.87 \pm 0.40\,\mu$m), 10 ($9.14 \pm 0.71\,\mu$m), 15 ($14.6 \pm 1.7\,\mu$m), and 20 μm ($22.0 \pm 2.7\,\mu$m), and the diameter of carbon particles were 6 ($5.29 \pm 0.94\,\mu$m) and 20 μm ($22.0 \pm 2.0\,\mu$m). The electrolyte solutions were 1.0 M KCl with pH 5.4 for polystyrene latex particles and 6.0 M $CaCl_2$ with pH 6.6 for carbon particles. These solutions had densities nearly equal to those of particles. Polystyrene is an insulator, but carbon is highly conductive than that of the medium. Further, we used yeasts and red blood cells (RBCs) as examples of biological particles. Common baker's yeasts were dispersed 1.0 M KCl solution with pH 7.1. Fresh human blood was sampled just prior to use and introduced into a vial that contained EDTA aqueous solution to prevent the aggregation of the cells. One drop of the blood sample was added to 100 ml of 0.155 M KCl solution with pH 6.6, which is almost isotonic with real blood.

2.3. Apparatus and measurements

Fig. 2 shows the capillary cell used in the present experiments. The cell was made of fused-silica capillary, which had a $100\,\mu\text{m} \times 100\,\mu\text{m}$ inner section and was 2 cm long, inserted to PTFE tubes with Ag|AgCl electrodes covered by heat-shrink tubes. The Ag|AgCl electrodes were made by electrolysis, at first; a silver wire ($d = 0.2$ mm) was connected to the anode of an electric power and the platinum wire with the cathode; both wires submerged in a solution of 1.0 M KCl. Then, a constant voltage (5 V) was applied for 5 min to make AgCl on the Ag wire. The migration of particles was observed by objective positioned upward. The focal point was set at the center of the capillary.

Fig. 3 shows the apparatus used in the experiments. A magnetic field was generated by a superconducting magnet (JMT, JMTD-10T100HH1, Japan). The cell was set on the holder in a homogeneous magnetic field. Sample solutions were provided to the capillary by a syringe pump. The flow rate was $5\,\mu\text{l}\,\text{h}^{-1}$. A galvanostat (Fusoh, HECS317, Japan) device or a potentiostat (Metronix, HSV1K-60, USA) device was used to provide a current. A current and a voltage were measured by an ammeter (Advantest, Digitalmultimeter R6551, Japan) and a voltmeter (Takedariken, Digitalmultimeter TR6843, Japan), respectively. A microscope attached to a charge-coupled device (CCD) camera (ELMO, ME421R, Japan) was used to observe the migration of particles and focused around center of the capillary to *z*-axis. The CCD image was displayed on monitor and also recorded on a videocassette. The migration velocity was measured from images captured in a computer.

When a particle in the flowed system, which was focused, was appeared in the observation region, a current was applied for several seconds and switched its direction reversibly before the particle reached the capillary wall. According to the alternatively switched current, the flowing particle migrated zigzag. Each migration distance perpendicular to the direction of the flow and the time for the migration were measured. Then, we calculated the migration velocity of a particle induced by the electromagnetic buoyancy.

We also found that the particle, when it was adsorbed at the capillary wall, could be desorbed by the electromagnetic buoyancy. In this observation, the flow was stopped. At first, a particle was adsorbed to the wall by the electromagnetic buoyancy, then desorbed by a reversed electromagnetic buoyancy by applying a reversed current. The desorption of particles was observed, when the current was increased from 0 to 1000 μA gradually at a fixed magnetic field of 10 T.

All measurements were carried out in a thermostated room at $25 \pm 1\,^{\circ}$C.

3. Results and discussion

3.1. Electromagnetophoretic velocity in flowing system

Fig. 4 displays an electromagnetophoretic behavior of a polystyrene latex particle with 20 μm diameter in the flow. The picture shown in Fig. 4 was made by superimposing images captured with 0.2 s intervals. The particle was moved by the flow from the right-hand side in Fig. 4. When a current was applied, the flowed particle underwent an

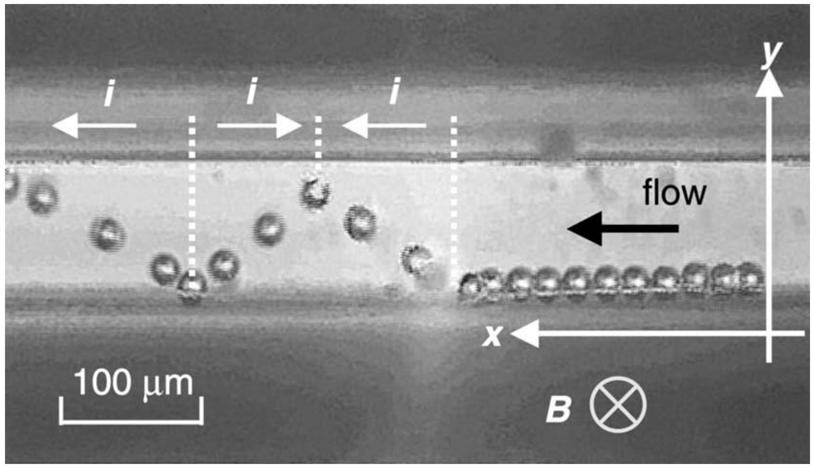

Fig. 4. Typical electromagnetophoretic behavior of a polystyrene particle in the flow. The diameter of the polystyrene particle was 20 μm. A 1.0 M KCl solution was used as a conductive medium. The magnetic field was 10 T and the current was 10 μA. The flow velocity was 5 μl h^{-1}. This picture was reconstructed from the images captured at a rate of five frames per seconds.

electromagnetophoretic force to the *y* direction. As a result, the particle moved diagonally to the direction of *x*-axis by the combination of the flow and the electromagnetophoretic force. Thus, when the direction of applied current was from the right-hand side to the left-hand side, the particle migrated to upward as shown in Fig. 4. When the direction of the applied current was switched before the particle reached to the capillary wall, the particle moved to the opposite direction. As the direction of the electromagnetophoretic migration of the particle was the direction of electromagnetic buoyancy, it proved that the electromagnetic buoyancy governed the electromagnetophoretic migration in the flow system in the same manner as observed in the closed cell [11]. Hence, the velocity of the electromagnetophoretic migration of the zigzagging particles was obtained as the component perpendicular to the direction of the flow (Fig. 4).

Fig. 5 shows the magnetic field dependency of the EMP migration velocity of polystyrene particles with 10 μm in diameter. As the magnetic field was increased from 3 to 10 T at a fixed current of 40 μA, the migration velocity increased proportionally to the magnetic field, as expected by Eq. (4).

Fig. 6 shows the current dependency of the EMP migration velocity of polystyrene particles, whose diameters were 20, 15, 10 and 6 μm. The magnetic field was 10 T and the applied current was in the range from 5 to 100 μA. The migration velocity was proportional to the current, as suggested from Eq. (4). It was also proved that a larger particle had a higher migration velocity.

The effect of the wall surface on the drag force for the particle cannot be neglect, when the distance from the surface is comparable to the particle radius. In the case of electromagnetophoresis in capillary flow system, as particles migrated zigzagging in the narrow channel, particles are under the influence of the friction due to the four walls. The effect of the surface on the motion of particle, migrating parallel and perpendicular to the wall, was considered by following

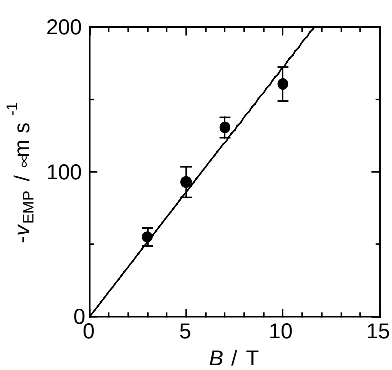

Fig. 5. EMP velocity of polystyrene particles increased in proportion with the applied magnetic fields. The current was 40 μA. The particle diameter was 10 μm. A 1.0 M KCl solution was used as a conductive medium.

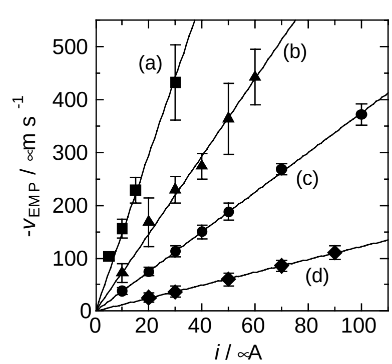

Fig. 6. EMP velocity of polystyrene particles at various applied currents. The magnitude of the homogeneous magnetic field was 10 T. The diameters of polystyrene particles were (a) 20 μm, (b) 15 μm, (c) 10 μm, and (d) 6 μm. A 1.0 M KCl solution was used as a conductive medium. The averaged value of the apparent conductivity of polystyrene, 0.0191 ± 0.0084 S cm^{-1}, was obtained from the slopes.

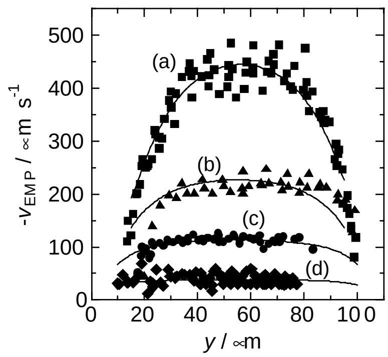

Fig. 7. EMP velocity of polystyrene particles at various y position when one wall position was $y = 0$. The magnitude of the homogeneous magnetic field was 10 T and the applied current was 30 μA. The diameters of polystyrene particles were (a) 20 μm, (b) 15 μm, (c) 10 μm, and (d) 6 μm. A 1.0 M KCl solution was used as a conductive medium.

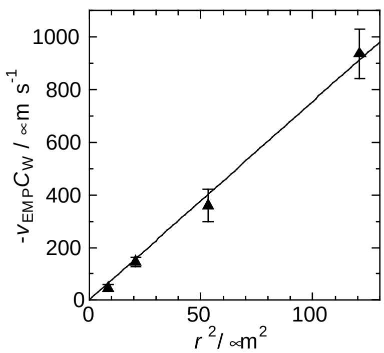

Fig. 8. The dependency of EMP velocity of polystyrene particles multiplied by the drag coefficient, C_W on the second power of particles' radius at various applied currents. The magnitude of the homogeneous magnetic field was 10 T. A 6.0 M $CaCl_2$ solution was used as a conductive medium.

equations. In the case that a particle moves along the center between parallel walls, the drag coefficient of the two walls, $C_{W,//}$, is expressed as:

$$C_{W,//} = \frac{1}{\left[1 - 1.004(r/h_z) + 0.418(r/h_z)^3 - 0.21(r/h_z)^4 - 0.169(r/h_z)^5\right]} \tag{5}$$

where h_z is the distance (m) between the center of the particle and the surface of the walls [12]. While the drag coefficient of a single wall perpendicular to the direction of migration, $C_{W,\perp}$, is expressed as:

$$C_{W,\perp} = \frac{1}{\left[1 - (9/8)(r/h_y) + (1/2)(r/h_y)^3\right]} \tag{6}$$

where h_y is the distance (m) between the center of the particle and the surface of the walls [12]. Here, to consider the influence of both walls, we used r/h_z defined by the equation:

$$\frac{r}{h_z} = \frac{r}{y_p} + \frac{r}{100 - y_p} \tag{7}$$

where y_p is the distance from the center of the particle to the wall, when it migrates perpendicular to the wall.

Fig. 7 shows the migration velocity of polystyrene particles in the y direction, when $y = 0$ is set on the surface of the one wall. The magnetic field was 10 T and the applied current was 30 μA. The migration velocity near the wall was lower than that around the center of the capillary. The lines were fitted ones using $C_{W,\perp}$ by Eqs. (6) and (7). As these curves gave good fits to the plots, it was found that the migration of micro-particles in the capillary was influenced by the capillary wall. Therefore, the drag coefficient due to the walls, C_W, could be given as the following equation:

$$C_W = C_{W,//} \times C_{W,\perp} \tag{8}$$

Fig. 8 shows the second power of polystyrene particles' radius dependency of the observed migration velocities shown in Fig. 7 multiplied by the drag coefficient of the wall C_W calculated by Eq. (8) using $h_z = 50$ μm, as C_W depends on R as shown in Eqs. (5) and (6). The EMP migration velocity is proportional to the second power of particles' radius. These results indicated that the dependency of the EMP velocity on B, i and r^2 is confirmed as expected from Eq. (4).

Fig. 9 shows the migration velocity of carbon particles whose diameter were 20 and 6 μm. The magnetic field was 10 T and the applied current was in the range from 5 to 90 μA. Although carbon particles have a higher conductivity than that of the medium, they migrated in the direction of the electromagnetic buoyancy, inconsistent with that expected from Eq. (4). The current dependency of the migration velocity of carbon particles was similar to that of polystyrene particles, though the migration velocity of carbon particles differs from that of polystyrene particles as shown in Fig. 6. The velocity of carbon particles was about nine times smaller than that of polystyrene particles, whose diameter was equal to the diameter of carbon particles.

Further, we tried the electomagnetophoretic migration of biological particles, such as yeasts and RBCs. The form of yeast was spherical and the diameter was determined as 7.17 ± 1.49 μm from the images captured in a computer. The real RBCs was not sphere, so we used a hypothetical

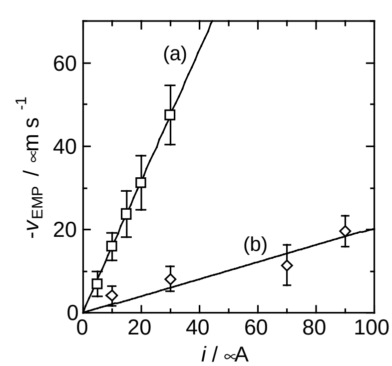

Fig. 9. EMP velocities of carbon particles, whose diameters were 20 μm (a) and 6 μm (b). The magnitude of the homogeneous magnetic field was 10 T. A 6.0 M $CaCl_2$ solution was used as conductive media for carbon particles. From the slopes, the apparent conductivity of $0.0668 \pm 0.0080\ \mathrm{S\,cm^{-1}}$ for carbon particles was determined.

Table 1
Apparent electric conductivity ($\sigma_{p,obs}$) and of polystyrene particle, carbon particle, yeasts and RBCs of diameter (d) estimated from the eletromagnetophoresis in the electrolyte solution with conductivity (σ_f)

Particle	Electrolyte solution	σ_f/S cm^{-1}	$\sigma_{p,obs}$/S cm^{-1}	σ_p/S cm^{-1}
Polystyrene	1.0 M KCl (pH 5.4)	0.112	0.0191 ± 0.0084	0
Carbon	6.0 M $CaCl_2$ (pH 6.6)	0.110	0.0668 ± 0.0080	727 [15]
Yeast	1.0 M KCl (pH 7.1)	0.112	0.0674 ± 0.0078	2×10^{-3} [16]
RBCs	0.155 M KCl (pH 6.3)	0.019	0.0107 ± 0.0011	6×10^{-3} [17]

radius, r', of RBCs estimated by the equation [13]:

$$r' = \left(\frac{3lV}{8A}\right)^{1/2} \quad (9)$$

where l is the characteristic length of the particle in the direction of the velocity and A the maximum cross section area perpendicular to the velocity. We used the recommended value of $r' = 4.25\,\mu$m [14]. Fig. 10 shows the migration velocities of yeasts and RBCs together with that of polystyrene particles, whose diameter was 10 μm. The magnetic field was 10 T and the applied current was in the range from 10 to 60 μA. The electromagnetophoretic behavior of the biological particles was similar to the manner of polystyrene particles, while the migration velocities of the biological particles were lower than that of polystyrene particle, and the deference was appeared between yeasts and RBCs.

3.2. Apparent conductivities of particles

The results in our experiments indicated that EMB played a predominant role in the migration of the micro-particles, regardless of the conductivity of the particles. Moreover, as the migration velocity of polystyrene particles in our experiments was 80% of the calculated one from Eq. (4) using $\sigma_p = 0$. These results suggest that particles are migrating not due to the intrinsic conductivity, but due to an apparent conductivity.

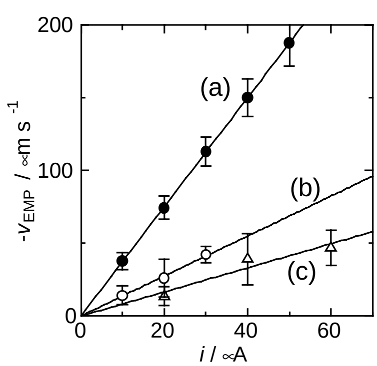

Fig. 10. Comparison of EMP velocities of biological particles, such as: (c) yeasts, (b) RBCs, and (a) polystyrene particles with 10 μm diameter whose diameter was similar to those of biological particles, the magnitude of the homogeneous magnetic field was 10 T. A 1.0 M KCl solution for polystyrene and yeast and a 0.155 M KCl solution for RBCs were used as conductive media. From the slopes, the apparent conductivities of 0.0674 ± 0.0078 S cm^{-1} and 0.0107 ± 0.0011 S cm^{-1} were determined for yeasts and RBCs, respectively.

Assuming that Eq. (4) can be applied to the present system, we could calculate the apparent conductivity of particles in each system. Table 1 summarizes the calculated conductivities of particles, $\sigma_{p,obs}$ based on Eq. (4) and intrinsic values, σ_p, from literatures. The result shows that polystyrene particles can be regarded as dielectrics, and that carbon particles have a much lower apparent conductivity than the intrinsic value. The apparent conductivities of yeast and RBCs were different from literature values. This suggests that the migration was governed by the surface conductivity on the particles. The electric charges on the surface of particles produce an electric double layer [18]. The effect of counter-ion cloud around the particles yields the surface conductivity on the particles. The values of $\sigma_p = 0.019$ S cm^{-1} for polystyrene particles and 0.067 S cm^{-1} for carbon particles seem to be comparable with the value of 0.025–0.050 S cm^{-1} reported for the surface of vesicles [19].

3.3. The desorption of particles from the capillary wall by EMP

The electromagnetophoretic force could desorb the particles adsorbed on the wall of the capillary, when the current was applied at a fixed magnetic field of 10 T. We could observe the desorption of polystyrene particles adsorbed on the capillary wall, whose diameter were 15 and 20 μm by the current of 549 and 311 μA, respectively. Carbon particles with 20 μm diameter were also desorbed from the capillary wall by the current of 327 μA. On the other hand, we could not observe the desorption of the smallest polystyrene particles with less than 10 μm diameter under the current less than 1 mA. However, if the current was increased more than 1 mA, polystyrene particles with a diameter of 10 μm could be desorbed.

Under the magnetic field of 10 T, we could get the EMP force enough for the desorption of micrometer-sized particles from the capillary wall. The forces required for the desorption was obtained from the experiments as 712 and 1327 pN for polystyrene particles with diameters of 15 and 20 μm, respectively, and 450 pN for carbon particles.

4. Conclusion

We demonstrated for the first time that the migration of micro-particles caused by the electromagnetic buoyancy could be observed in the open flow system. We also observed that carbon particles with a higher conductivity than the medium migrated to the direction of electromagnetic buoyancy as same as observed in polystyrene particles, which had a lower conductivity than the medium. This proved that there is no electric current in carbon particles. Thus, the migration velocity depended on both particle diameter and the surface conductivity. Further, we could observe that biological particles, such as yeasts and RBCs, migrated and the migration velocity of yeasts was higher than that of RBCs. Conclusively, the possibility to separate particles, e.g. biological cells, due to their sizes and surface conductivities was strongly promised. Moreover, it was found that the EMP force was sufficient to desorb particles from the capillary wall in the magnetic field of 10 T. Thus, the electromagnetophoresis is highly promising as a new method to measure an interaction force between a particle and a wall at the pN level, which is sensitive three orders than the conventional AFM.

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