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Study of micro-plastics separation from sea water with electro-magnetic force

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Abstract

The method of removing micro-plastics from sea water has been developed using electro-magnetic force. Plastics are difficult to decompose and put a great load on the marine environment. Especially a plastic with a size of 5 mm or less is defined as micro-plastic and are carried by ocean currents over long distances, causing global pollution. These are not easily decomposed in the natural environment. The Lorentz force was generated in simulated sea water and its reaction force was applied to the micro-plastic to control their motion. Lorentz force was generated downward and the reaction force to the plastics was upward. The plastic used in the experiment was polystyrene with a diameter of 6 mm, and the density was 1.07 g/cm3. The polystyrene sphere levitated at the current density of 0.83 A/cm^2 and the external field of 0.87T. The particle trajectory calculation was also made to design separation system using superconducting magnet.

Keywords: micro-plastics, Lorentz force, reaction force, motion control

1. INTRODUCTION

In recent years, a large amount of plastic waste has been generated in the sea due to illegal dumping and damage of fishing equipment during use [1]. The generated marine plastic rides on the ocean current, drifts and is washed ashore up on the coast and is re-flowed into sea as micro-plastics made by waves together with the ultraviolet ray from sunlight on the coast. The microplastic is defined as plastic waste smaller than 5 mm. Polyethylene, polypropylene and polystyrene are most of them [2]. These are difficult to decompose in the natural environment and their size and density are small and hence are carried by ocean currents over long distances. This is the reason why they have caused a global problem. Especially in Asia it has been pointed out that the marine concentration of micro-plastics is high [3].

In addition, harmful chemical substances such as persistent organic pollutants (POPs) adhere to the micro-plastics. (Stockholm Convention was adopted to prevent pollution of the global environment for eliminating or reducing POPs. [4].) POPs usually adhere to micro-plastics at high concentration (10^5-10^6 times higher than the surrounding seawater) due to their hydrophobic characteristics [5].

Fish and shellfish misunderstand them as plankton and likely intake them. For this reason, POPs are bioaccumulated by the food chain in the fish and shellfish. It means that there is a concern that humans may ingest fish and shellfish containing the POPs which may affect the human body. Though no effects on the human body have been reported at this time [6], considering the potential danger, early recovery of microplastics is desired.

Each country has been carrying out to reduce plastic waste. In Japan, various measures are being taken, such as increasing the recycling efficiency of plastics and using biodegradable plastics [7]. However, it is difficult to collect plastic waste that has already flowed out into the ocean and especially concerning micro-plastics, it cannot be said that the collection method is being studied.

Therefore, we decided our ultimate target to recover potentially dangerous microplastics. When it comes to the actual recovery of microplastics from ocean, the scale is too large to recover realistically.

We focused on onshore aquaculture farms that are connected to part of the hot effluent of nuclear or thermal power plants. These farms mix the warm effluent from power plants with natural seawater to bring to an appropriate temperature for aquaculture. For this reason, microplastics also exist in aquaculture water at farms. If the micro-plastics can be removed, it is expected that safe and secure seafood can be provided.

At present, the only method for removing microplastics is to control the dumping of plastics as described above. Therefore, it can be said that the development of a method for separating and removing potentially dangerous microplastics from sea water is an urgent issue. Therefore, in this study, we examined a method for separating and removing microplastics and one of the results will be reported.

2. EXPERIMENTALS

2.1 Micro-plastics

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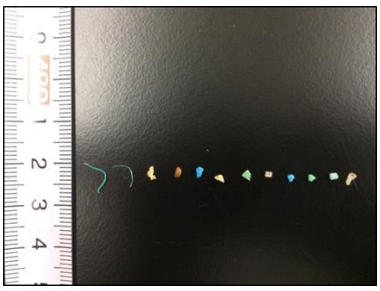

Fig.1. Microplastics collected from the sea.

Prior to the experiment, it was confirmed whether or not micro-plastics actually exist in the ocean. Fig. 1 shows a photograph of the micro-plastic actually taken from the seawater of the fishing port. These were collected at the Takasu fishing port. Seawater was pumped up at about 200 L / min for 90 minutes and 44 micro-plastics were collected. It means the concentration of micro-plastics approximately 2.5 pieces / m^3.

2.2. Theory

In this study, Lorentz force was used as a method for separating and removing micro-plastics in the ocean. The method using Lorentz force can be a suitable method because seawater would not be contaminated by adding chemicals and hence the treated seawater can be drained without purifying after separation and removing of micro-plastics.

Suppose the condition in which a current is flowing through a medium under a magnetic field. When the current (current density J ($A/m2$)) flows in the direction perpendicular to the magnetic field B (T), the Lorentz force F (N) is induced in the medium, and the force is expressed by the following equation (1).

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} \tag{1}$$

The situation is shown in Fig. 2 (a). In this case, the magnetic field is applied in the perpendicular direction to the paper surface. Here, there is an insulating sphere exists in the medium. Lorentz force is not induced to the sphere because no current flows through this insulating sphere. Therefore, the Lorentz force is induced only to the medium. When the medium is confined, the Lorentz force becomes hydrostatic pressure in the media.

On the other hand, for the insulated sphere, the pressure of the surrounding medium rises and hence a reaction force of Lorentz force is applied, that is buoyancy. The situation is shown in Fig. 2 (b). As a result, the insulating ball will float when the Lorentz force is sufficiently large. This buoyancy is derived by Leenov and is expressed by equation (2) [8] . We tried to capture and recover micro-plastics using this buoyancy.

$$\boldsymbol{F_E} = -\frac{3}{4} \mathrm{V} \, (\boldsymbol{J} \times \boldsymbol{B}) \tag{2}$$

2.3. Experimentals

A flow path was prepared and a saline solution (density: 1.03 g / cm^3) having a concentration of 3.4%, that imitated seawater, was flowed through this flow path, and an experiment was conducted. The Halbach magnet was placed close to the flow path, and two electrodes were placed in the flow path at a distance of 30 mm so as to be perpendicular to the flow path. The magnetic field between the electrodes in the device averaged 0.87T. The flow path is made of acrylic and measures 25mm x 17mm x 565 mm. The electrodes are made of stainless steel mesh with a wire diameter of 0.15 mm, 39 mesh, 0.65 mm pitch, and aperture ratio of 77% (mesh / pitch). The plastic test piece used in the experiment was a polystyrene sphere (density 1.07 g / cm^3) with a diameter of 6 mm.

The reason for using the mesh electrode in this experiment is not to disturb the flow in the flow path. In the practical application the magnetic field is differently arranged. A solenoid coil will be used so that the electrodes can be arranged parallel to the flow.

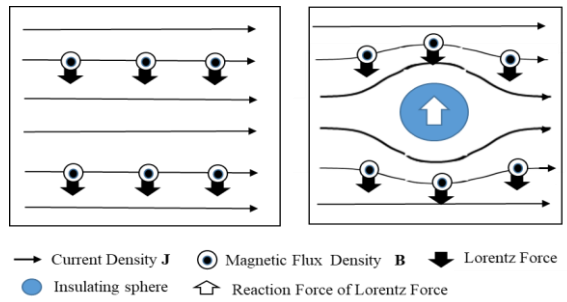

Fig. 2. Generated Lorentz force (a) when no insulating sphere exists and (b) when an insulating sphere exists.

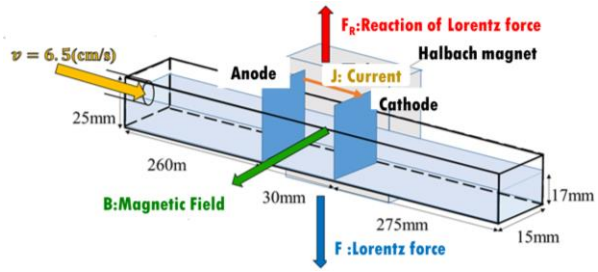

Fig. 3. Schematic diagram of the experimental system.

3. RESULTS AND DISCUSSION

3.1. Results of plastic spheres

Fig. 4 shows the levitation of polystyrene spheres at a current density of 0.83 A / cm^2 and a flow velocity of 6.5 cm / s. It can be seen that the plastic sphere is floated by Lorentz force and is carried downstream by the flow. The magnetic flux density was set to 0.87 T and the flow velocity was set to 6.5 cm / s. The experiment was repeated with changing the current density. The current density at which polystyrene spheres float was determined to be 0.08 A / cm^2. However, this value was larger than the calculated result obtained from (2).

On the other hand, in the experiment when the flow velocity was 0 cm / s, polystyrene was floated at the current density of 0.05 A / cm^2. It was confirmed that this current density was almost the same as the calculated figure by (2).

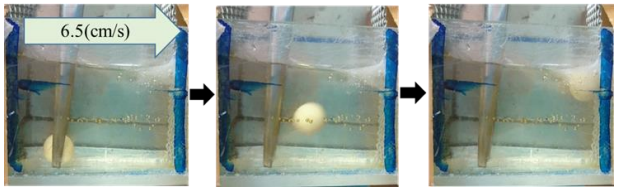

Fig. 4. Polystyrene sphere levitation (flow velocity 6.5 cm / s , current density 0.83 A / cm^2).

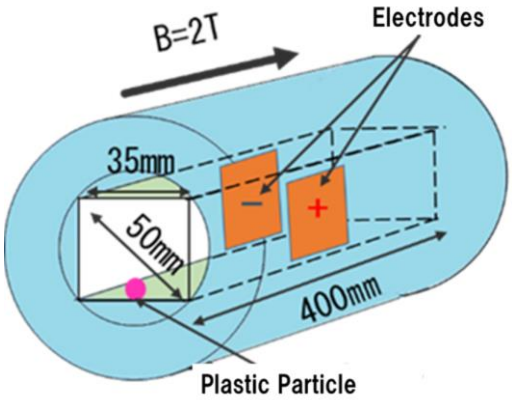

Fig. 5. Schematic diagram of the experimental equipment.

3.2. Device Design

Fig.5 shows a schematic diagram of the assumed experimental equipment. In this system a superconducting magnet is to be used. In a room temperature bore of 50 mm in diameter and a central magnetic flux density of 3 T, a square sectional pipe (35mm x 35mm x 400 mm) is installed and seawater flows in the X-axis direction in the pipe. A current and a magnetic field are applied to the pipe as shown in the figure to induce Lorentz force.

The trajectory of the particles after the plastic sphere was left to stand at the bottom of the flow path was calculated. The calculation was performed by solving the equations of motion in the Z and X directions with time evolution. The Z direction is vertically upward, and the X direction is the longitudinal direction of the magnet. The seawater flows in X direction. The equations of motion are shown in (3) and (4),

$$\boldsymbol{F}_z = 3/4\ \mathrm{V(J \times B)} - m\boldsymbol{g} + \rho V\boldsymbol{g} - 6\pi\eta r v_z \quad (3)$$

$$\boldsymbol{F}_x = 6\pi\eta r(v_{fx} - v_x) \quad (4)$$

here, m is mass of particle, V is volume of the plastic, r is particle radius, v_z particle velocity in Z direction, v_x is particle velocity in X direction, η is viscosity of seawater, g is gravitational acceleration, and v_{fx} is fluid velocity in X direction.

First, (3) in the Z direction will be explained. The first term on the right side is the reaction force from Lorenz force in the upward direction and is positive. The 2nd and 3rd term represents gravity and buoyancy, respectively. The last 4th term is the drag force from the fluid, which is the resistance force from fluid during the particle moving in the fluid at the velocity of v_z.

Then (4) in the X direction will be explained. Since the X direction is only the drag force, the electromagnetic force does not work. v_{fx} is the flow velocity of the medium, which changes depending on the position in the Z direction.

The time dependence of the position was obtained by solving the equation of motion using the Euler method in Z and X directions. Furthermore, the Z-X relationship was derived from those solutions and the particle trajectory was obtained. The particle trajectory was calculated for polystyrene sphere with diameters of 6 mm, 4 mm, and 1 mm, respectively. The magnitude of $\boldsymbol{J} \times \boldsymbol{B}$ were changed to calculate how large it should be needed to separate the particle. The density of polystyrene used in the calculation was 1.04×10^3 kg / m^3, the size of the electrode was 40 mm and the average flow velocity was about 1 m / s. The processing amount in this system was set at 1.2 kg / sec.

The separation plate was placed horizontally at the position of 20 mm from the bottom and of 100 mm downstream. The particles that reached above the separation plate were thought to be separated. The flow velocity distribution in the X direction was considered as a parabolic shape that differs depending on the position of Z as shown in Fig. 6. The flow velocity distribution was given by the following equations,

$$U(z) = U_{max}\big(z(2H - z)\big)/H^2 \quad (5)$$

$$U_m = 2/3\ U_{max} \quad (6)$$

where U(z)is velocity at z, U_{max} is the largest velocity, 2H is height of flow channel 35mm, U_m is average flow speed. Umax can be calculated by Um, defined as the processing speed.

Fig. 7 shows the trajectories of polystyrene with J × B of 0.7×10^3(N / m^3 e.g. 0.14 A / ㎠, 0.5T) and diameters of 6 mm, 4 mm, and 1 mm, respectively. The electrode exists at the position from -0.02 m to 0.02mm in the X direction in the figure. The figure shows that the particles are floated by the reaction force of the Lorentz force at the electrodes and are carried downstream. Since the levitation force disappears outside of the electrodes sedimentation of particle begins. However, the motion of the particle differs depending on the size. When the particle having a diameter of 6 mm reaches at the electrodes, it is levitated and reaches the ceiling of the flow path and then settles. The particle reaches above the separation plate and then can be separated. Concerning 4 mm and 1 mm particle cannot reach above the separation plate, which means that they cannot be separated.

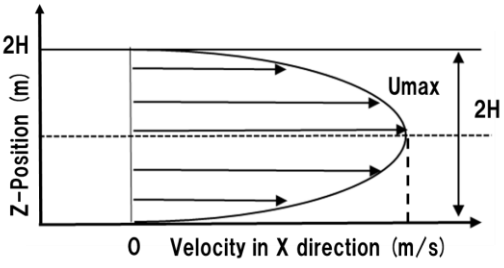

Fig. 6. Parabolic flow velocity distribution.

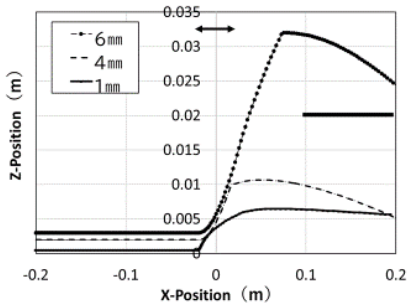

Fig. 7. Polystyrene particle trajectories with diameters of 6 mm, 4 mm, and 1 mm. The electrodes are between the arrows. The position of the separation plate is indicated by a thick line on the right side.

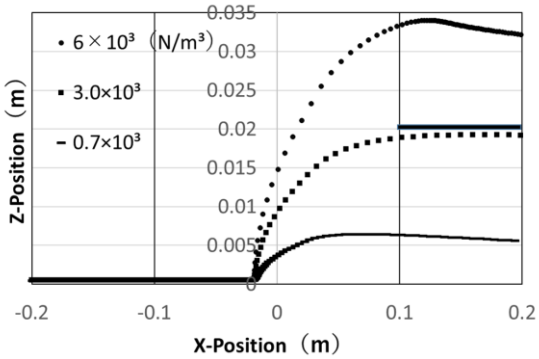

Fig. 8. Particle trajectories with a diameter of 1 mm. The electrodes are located from -0.02m to 0.02 m. The position of the separator is shown by a thick line on the right side.

The value of JxB was changed in order to find the condition to separate 1 mm diameter particle. Because the particle with larger size can be separated with the condition where 1 mm particle can be separated.

Fig. 8 shows trajectories of particle having a diameter of 1 mm with different magnitude of J × B. The electrode exists at the position from -0.02 m to 0.02 m in the X direction just like in the fig.7. The magnitude of J × B are 6.0×10^3(N / m³), 1.5×10^3(N / m³), and 0.7×10^3(N / m³ T). Each JxB magnitude corresponds (1.2 A / cm², 5T), (0.3 A / cm², 5T), and (0.35A / ㎠, 2T), respectively. It can be seen that when the magnitude of J × B is 6.0×10^3(N / m³), particles with a diameter of 1 mm can be separated. However, since there is a possibility of electrolysis of seawater at 1.2 A / cm², it is considered that electrolysis can be avoided by reducing the current density. In this case the flow velocity should be reduced to separate the particle.

4. CONCLUSION

We examined the separation of micro-plastics from the ocean using Lorentz force, and the conceptual calculation was made aiming at the practical use of the system. When the processing amount was 1.2 kg / sec, it was possible to separate polystyrene with a diameter of larger than 4 mm at 0.7 x 10^3N / m³ of JxB . For 1mm polystyrene 6.0×10^3N / m³ or higher JxB is needed. It is possible to reduce JxB by decreasing the processing speed.

In the future, it will be necessary to study following three points: electrolysis, change of particle size and shape. For the first point, it is necessary to limit the current density to the range of that does not cause electrolysis, or to change the electrodes to reduce the generation of chlorine, which is a cause of corrosion and add some equipment to treat other gases such as hydrogen. For the second point, we will clarify the relationship between particle size including micrometer-order and separation efficiency with changing the parameters such as current density, applied magnetic field, and electrode size. For the third point, we will examine the behavior of various shapes samples such as thread-like and plate-like etc. and estimate the impact on the separation efficiency.

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