Microplastic Collection with Ultra-High Magnetic Field Magnet by Magnetic Separation

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***Abstract*— In recent years, the increase of microplastics (MPs) in ocean have been recognized as one of ocean pollution listed in Sustainable Development Goals (SDGs). Since MPs absorb harmful chemicals while floating in ocean, small fish which eats the absorbed MPs may fall into bad digestion and poor health condition. To solve the ocean pollution problem, a good MP collection method must be proposed with a high processing speed and a high MP collection ability. While, recently, the performances of 2nd generation high-temperature superconducting (HTS) magnets which can generate a field higher than 15 T have been improved. It is expected that MP collection performances are enhanced with such high field superconducting magnets.**

In this paper, we propose a conceptual design for MP collector from seawater using superconducting magnets. To evaluate the performances of the device, we developed a fluid simulation coupled with magnetic field simulation. The simulation results indicate that MPs can effectively be collected with a high magnetic field with a high processing speed.

***Index Terms*—microplastic, particle fluid simulation, SDGs, superconducting magnets.**

I. Introduction

MICROPLASTICS (MPs) in the ocean environment are a kind of serious environmental pollution. Many journal papers have reported potential influences on the ocean and even terrestrial environment [1], [2]. MPs are, in common, plastic fragments with a diameter smaller than 5 mm. Since chemicals easily stick to MPs, MPs behave as a carrier of harmful substances such as Poly Chlorinated Biphenyl (PCB). Small fish or crustaceans eat the polluted MPs, and this may result in bad digestion or deterioration of the health conditions [3], [4]. Since the number of MPs has been increasing [5], the development of MP collection method from the ocean is an urgent task towards the United Nations (UN) Sustainable Development Goals (SDGs) [6].

Several methods for MP collection have already been proposed, such as collections by floatation [7], ultrasonic [8], and filter, and their purpose is industrial wastewater purification. However, these methods are not capable of processing a large amount of seawater. One promising solution is a way to use a strong magnetic field with high gradient, *i.e.*, a magnetic separation. When a strong magnetic field with high gradient is applied to water containing MPs, MPs experience a large magnetic force compared to water. Meanwhile, in the recent years, the performances of high-temperature superconducting (HTS) magnets have been enhanced. Currently, some >15-T class HTS magnets are under development, and such magnets will be applicable to MP collectors from ocean.

In this paper, we propose a conceptual design of an MP collector from ocean environment using a high field HTS magnet. To evaluate the performance of the proposed system, we have developed a fluid simulation code based on a particle method, coupled with magnetic field analysis. The simulation results demonstrate the high separation performance of the collector with a high field HTS magnet. The high field is effective in MP collection from seawater.

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II. Conceptual Design of MP Collector

Fig. 1 shows the schematic view of the proposed MP collector. The MP collector consists of a tank and a high field HTS magnet. The tank is placed horizontally, and the seawater is injected from the left inlet of the tank. Most of the injected seawater is discharged from the right bottom outlet of the tank. A few pairs of HTS coils are placed so that a strong field with a high gradient is applied to the tank vertically. Since the MPs experience upward forces by the strong field with the high gradient in the tank, much of MPs would be separated toward the top outlet.

To investigate the performances of the proposed MP collector, we define two indices: (1) MP collection ratio and (2) MP fragment density. These performances were simulated by a method mentioned in the next chapter.

III. Simulation Method

To evaluate the performance of the proposed MP collector, we have developed a fluid analysis code coupled with magnetic analysis. As the fluid simulation, a particle method is adopted [9]. The particle method is one of mesh free methods, and its advantages are fast computation and easy implementation. The seawater containing MP fragments is presented by many fluid

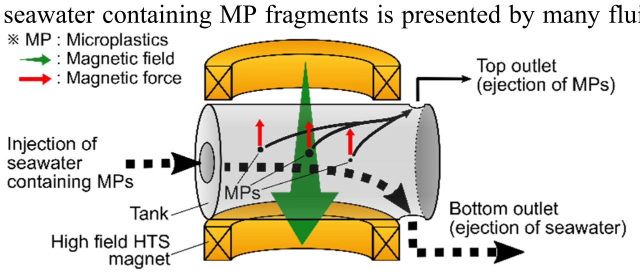

Fig. 1. Schematic view of proposed microplastic (MP) collector. Seawater is injected from left side and ejected from outlet at right bottom. The MPs experience upward magnetic force by the magnetic field and ejected from top outlet.

particles. In this paper, the seawater particle free from MP segments is called "SWP (seawater particle)." Meanwhile, the seawater particle containing MP fragments is named "MPP (microplastic particle)." An MPP contains 20 MP fragments in this simulation to reduce computation time (see the inset of Fig. 3(a)). These SWP and MPP have different properties.

Every fluid particle (SWP & MPP) moves according to the Navier-Stokes and the continuity equations with Lagrangian derivative $\mathrm{D}/\mathrm{D}t$:

$$\frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\boldsymbol{u} + \boldsymbol{f}_{\mathrm{ex}} \tag{1}$$

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = 0 \tag{2}$$

where $\boldsymbol{u}$, t, ρ, P, ν, and $\boldsymbol{f}_{\mathrm{ex}}$ are the particle velocity, the time, the density, the pressure, the kinematic viscosity, and the external force per volume, respectively. Equation (1) is solved with a semi-implicit method. First, the viscous and external-force terms are computed explicitly. Second, the pressure is computed implicitly so that the density spatial-variation is zero. Here, the zero spatial-variation is derived from no temporal-variation of (2) and the initial condition. By computing the pressure gradient in (1), the behavior of fluid particles is simulated. The differential terms are computed with the weighted average of the physical values within the kernel radius. In this simulation, the kernel function shown in [10] is employed. Some techniques are incorporated to improve the simulation accuracy, such as a high-order source term [11] and a higher-order Laplacian [12].

For a magnetic force acting on SWP and MPP, the formula is presented as follows:

$$\boldsymbol{f}_{\mathbf{mag}} = \frac{\chi}{\mu_0}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B} \tag{3}$$

where χ, μ_0, and $\boldsymbol{B}$ represent the magnetic susceptibility, the magnetic permeability of free space, and the magnetic field, respectively. The equation means that a magnetic force is proportional to field intensity and its gradient. $\boldsymbol{f}_{\mathrm{ex}}$ in (1) corresponds to the magnetic force $\boldsymbol{f}_{\mathbf{mag}}$ plus the gravity force $\boldsymbol{f}_{\mathrm{g}}$ ($\boldsymbol{f}_{\mathrm{ex}} = \boldsymbol{f}_{\mathbf{mag}} + \boldsymbol{f}_{\mathrm{g}}$) in this paper. The magnetic susceptibility of SWP and MPP is supposed not to be saturated.

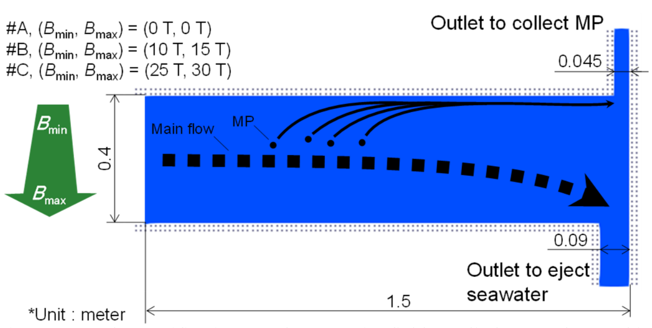

Fig. 2. Tank specifications and magnetic field applied to tank. In this simulation, magnetic field is supposed to change with constant gradient from B_{min} to B_{max}.

IV. Simulation Results

The MP collector with dimensions shown in Fig. 2 were simulated under the conditions listed in Table I. The "polluted seawater," which means the seawater containing the MP fragments (SWP & MPP) in this paper, is injected with the flow velocity of 0.5 m/s through the inlet with a diameter of 0.4 m. The MP fragment density in the injected polluted seawater is 3864 m^{-2}; *i.e.*, 773 MPPs are injected to the tank per second.

In this simulation, for simplicity, a magnetic field spatially changes with a constant gradient from B_{min} on the top to B_{max} on the bottom of the tank. The field gradient along the tank-longitudinal direction due to a real magnet configuration is ignored for simplicity, because this work is now on the

TABLE I
Tank Specifications and Operating Conditions

Parameters	Values
Length; height of tank [m]	1.0; 0.4
Inlet diameter [m]	0.4
Top outlet diameter [m]	0.045
Bottom outlet diameter [m]	0.09
Fluid particle (SWP & MPP) radius [mm]	15
MP fragment radius [mm]	3.0
Number of MP fragments in an MPP	20
Magnetic susceptibility of MPP	-6.89×10^{-5}
Magnetic susceptibility of SWP	-9.05×10^{-6}
Density of MPP [$\mathrm{kg/m^3}$]	943
Density of SWP [$\mathrm{kg/m^3}$]	1000
Flow velocity of injected polluted seawater [m/s]	0.5
Amount of injected polluted seawater per unit time [$\mathrm{m^2/s}$]	0.19
Number density of MPs in polluted seawater [$\mathrm{m^{-2}}$]	3864
Number of injected MPs per second [$\mathrm{s^{-1}}$]	773
Magnetic field gradient [T/m]	12.5
Magnetic field (B_{min}, B_{max}) [T]	Case A: (0, 0)
	Case B: (5, 10)
	Case C: (10, 15)

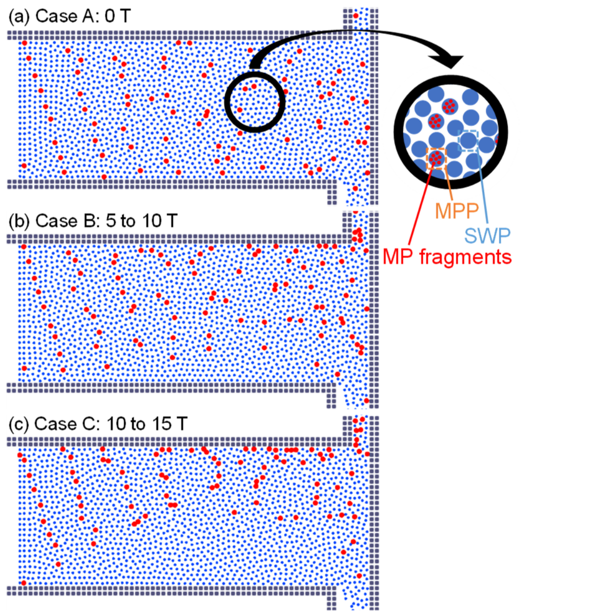

Fig. 3. MPP distribution inside the MP collector in cases of (a) 0 T, (b) 5 to 10 T, and (c) 10 to 15 T. Blue particles represent SWPs and red ones MPPs. Most of MPPs gather upwards due to a high magnetic field in case C.

feasibility study stage. Three different magnetic fields applied to the tank were investigated in this paper: (1) no magnetic field (case A); (2) 5 to 10 T (case B); and (3) 10 to 15 T (case C).

As indices of collection performances, we introduce the "MP collection ratio" and the "MP fragment density." The MP collection ratio β indicates how much MP fragments are collected from the top outlet. The MP fragment density is the number of ejected MP fragments per the unit polluted seawater ejected through the outlets. A high-performance MP collector reveals a high MP collection ratio and a high MP density at the top outlet.

A. *MPP distribution and magnetic force in tank*

Fig. 3 shows the MPP distribution in the tank at 60 s after the start of operation. Red particles are the MPP, and blue particles are the SWP. When no magnetic field is applied, the MPPs diffuse and distribute uniformly as shown in Fig. 3(a). Since the aperture of the bottom outlet is larger than that of the top outlet and the gravity force is applied downward, most of the fluid particles (SWPs and MPPs) are discharged from the bottom outlet. In Fig. 3(b), the MPPs keep moving slightly upward due to the applied field of 5 to 10 T (case B) while the fluid particles move from the left to the right ends. When the magnetic field of 10 to 15 T is applied (case C), as shown in Fig. 3(c), the greater number of MPPs gather on the upper wall, and a large part of the injected MPPs are discharged from the top outlet with a small amount of SWPs. However, the small number of MPPs still flow out of the bottom outlet.

Fig. 4 depicts the distributions of magnetic force which the MPPs experience. From the top to the bottom, the magnetic force intensity increases. In the case B, an MPP experiences an upward force density of 3410 N/m^3 on the top wall. This force intensity is too small to well separate MPPs when the gravity force intensity of 8927 N/m^3 works in the downward direction. Whereas, in the case C, an MPP experiences 10250 N/m^3 on the bottom walls. The value is sufficiently larger than the gravity force, hence the magnetic field is large enough to separate MPPs to the top outlet. The SWP itself is also diamagnetic with the 7.6 times smaller magnetic susceptibility than that of MPP. Therefore, since the upward force to SWPs is enough small, most of the SWPs is discharged from the bottom outlet.

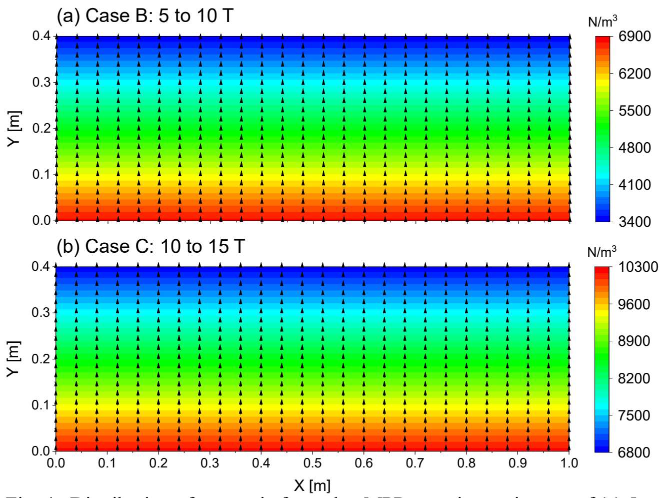

Fig. 4. Distribution of magnetic force that MPP experiences in case of (a) 5 to 10 T and (b) 10 to 15 T. MPPs are subject to magnetic force 7.6 times larger than that of SWPs.

B. *MP collection ratio*

Fig. 5 shows the time transient of the accumulated numbers of MPPs ejected from the top or the bottom outlets. At $t = 0$ s, the injection of MPPs to the collector starts, and the first particles flow out from $t = 2.6$ s, reaching the outlets. The accumulated number of ejected MPPs changes linearly with time for all the cases.

With no magnetic field (case A), almost 100 % of injected polluted seawater (SWP & MPP) flows out of the bottom outlet due to the gravity force as well as the large aperture of the bottom outlet. When the magnetic field with 5 to 10 T are applied (case B), a small part of the injected MPPs flow out of the top outlet. However, most of the injected MPPs are still discharged from the bottom outlet. Whereas, when the higher magnetic field is applied (case C), more than half of the injected MPPs flow out of the top outlet.

Here, we investigated the "MP collection ratio" defined as follows:

$$\beta = \frac{n_{\mathrm{top}}}{n_{\mathrm{top}} + n_{\mathrm{bottom}}} \times 100\ \% \tag{4}$$

where n_{top} and n_{bottom} are the numbers of ejected MP fragments per second from the top and the bottom outlets.

Fig. 6 shows the number of ejected MP fragments per second in the cases A, B, and C. It is clearly seen that the strength of applied magnetic field increases the MP collection ratio β. As stated, all the MPPs are discharged from the bottom outlet in case A, that is, the collection ratio is ~0%. In case B, the MP collection ratio is 25%; however, it increases to 62% when the gradient field of 10 to 15 T is applied (case C).

It is clear that a high field increases a MP collection ratio.

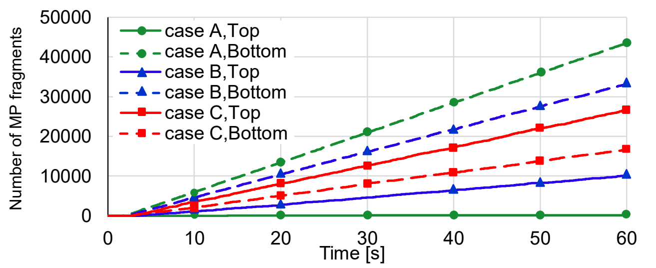

Fig. 5. Time versus accumulated number of ejected MP fragments. MP fragments are ejected with a constant rate.

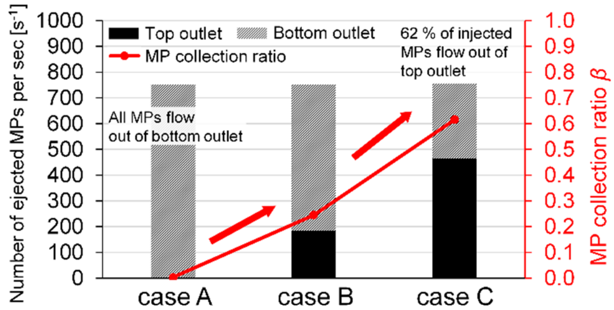

Fig. 6. Number of ejected MP fragments per second and MP collection ratio in cases of A, B, and C.

C. *MP fragment density*

As water is also diamagnetic and experiences an upward magnetic force, a high magnetic field increases the number of SWPs discharged from the top outlets. This may decrease the MP fragment density of top discharged fluid particles. Fig. 7 shows the amount of the seawater excluding MP fragments at the top and the bottom outlets. Here, all the injected fluid particles are discharged from top or bottom outlet because of the incompressibility of water. In case A, no SWP is ejected from the top outlet. The number of the SWPs discharged from the top outlet slightly increases with increase in the strength of magnetic field. A too strong magnetic field may cause decreasing the MP fragment density. Therefore, an adequate high magnetic field is preferred for a high MP fragment density.

Fig. 8 shows the MP fragment density of the fluid particles discharged from the top and the bottom outlets. In case A, the MP fragment density at the top outlet is smaller than that at the bottom outlet. Whereas, by applying a magnetic field, the MP fragment density of the ejected fluid particles at the top outlet increases dramatically. In case B, the MP density on the top outlet is over 20000 m^{-2}; and 31470 m^{-2} in case C. It is approximately 8 times larger than the MP density of the injected polluted seawater.

From the simulation result, the magnetic field of 10 - 15 T is not so high that the MP fragment density decreases.

V. Long Tank Model

In the previous 1.0-m length model of case C, only ~60% of the injected MPPs come out of the top outlet. In Fig. 3(c), some MPPs do not reach onto the upper wall before moving to the right end of the tank. The reason is the short length of the tank where MPPs experience a magnetic force. The MP collection performance would be improved by lengthening the tank.

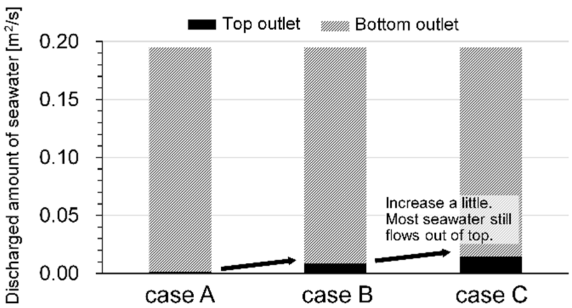

Fig. 7. Amount of seawater discharged from top and bottom outlet per unit time.

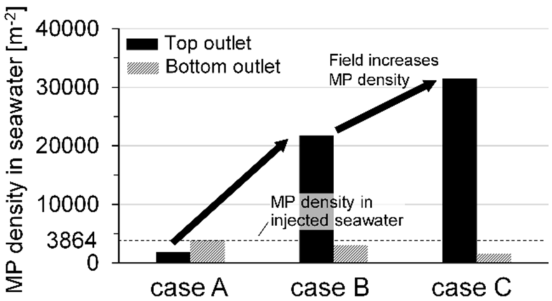

Fig. 8. MP densities of top and bottom outlets for three different fields.

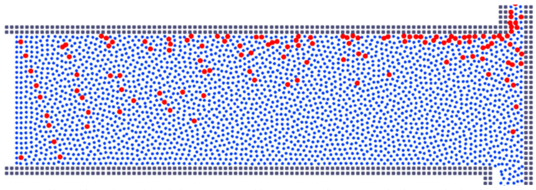

Fig. 9. MP distribution inside MP collector when tank length is lengthened.

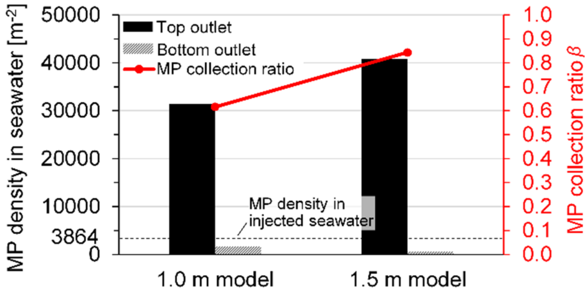

Fig. 10. MP density in discharged seawater and MP collection ratio for 1.0 m and 1.5 m long model.

Fig. 9 shows the simulated MPP distribution of 1.5-m length model with a magnetic field that spatially changes 10 to 15 T. The greater number of MPPs concentrate onto the upper wall before reaching the right end of the tank. Then, almost all MPPs are ejected through the top outlet. Fig. 9 clearly shows that the amount of MPPs flowing out of the bottom outlet drastically decreases.

The MP collection ratio and the MP fragment density of discharged fluid particles are shown in Fig. 10. The MP collection ratio increases to 84%. The longer the tank length or the higher the magnetic field is, the higher the ratio is. The MP fragment density of the fluid particles discharged from the top outlet is also improved. In the 1.5-m length model, the MP fragment density increases 10 times compared with that of the injected polluted seawater.

The magnetic field intensity and its gradient are important parameters to improve the collection performance. A long tank is also effective for the performance improvement.

VI. Conclusion

In this paper, we propose a conceptual idea for microplastic (MP) collection in the ocean environment by a magnetic separation with high magnetic field. A particle method is developed as a fluid simulation, and it is combined with magnetic force simulation. In this paper, three different magnetic fields are simulated; no magnetic field (case A), a field that spatially changed from 5 to 10 T (case B), and from 10 to 15 T (case C). As the result, 62% of the injected MP fragments are ejected from the top outlet together with a small amount of seawater. That is, the MP fragments can effectively be collected with a high magnetic field. Furthermore, an MP collection performance are improved by prolonging the tank. The MP collection ratio increases from 62% to 82%. High fields are a promising candidate for MP collection from seawater.

In this work, we demonstrate the feasibility of the proposed collection system. Since the field requirements are also clarified, as a next step, we will optimally design REBCO coils to generate a strong field with ideal high gradient.

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