Improvement in MHD Separation Device for Separation of Oil from Oil-Contaminated Seawater Using High-Field Superconducting Magnet*

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Abstract

A unique device for separating oil from oil-contaminated seawater by the magnetohydrodynamics (MHD) method, so-called the MHD separation device, is improved on the basis of the results of observation of the inside of MHD separation cells. The MHD method is based on the difference in electric conductivity between seawater and oil; the separation force applied to oil as a reaction of the electromagnetic force is used for oil separation. The performance of the improved device with a mixture of artificial seawater and simulation particles instead of oil droplets is tested using a 10-T class superconducting magnet. The results show perfect separation at a magnetic field of 5 T / 0.1 A or higher.

1. Introduction

Recently, leakage of heavy oil and crude oil due to collision and stranding of oil tankers has become a serious problem. As the marine environment has been seriously affected by such oil leakage, a method of rapidly separating oil from oil-contaminated seawater is desired [1]. A new method of oil separation based on electromagnetic force, the so-called magnetohydrodynamics (MHD) method, has been designed and tested [2,3]; the MHD method of oil separation utilizes a high magnetic field from a superconducting magnet and an electric current passed through seawater. In comparison with the conventional method that uses magnetic powders, the MHD method has the advantages of facilitating treatment of separated oil and of having little effect on the environment.

In a previous experiment [2] using simulation particles which have specific gravity similar to oil and very low electric conductivity instead of oil droplets mixed with artificial seawater, a high separation ratio (0.9) was obtained when the magnetic field was 10 T and the electric current was 0.4 A. However, the separation ratio was still smaller than the theoretical value (1: perfect separation). It was also reported that there are problems of the occurrence of vortices and blockage of particle clusters inside the MHD separation cell. The purpose of the present work is to clarify the cause of the problems by observing the inside of the

MHD separation cell using a high-speed video camera. In addition, the MHD separation device is improved on the basis of the observation results, and the performance of the improved device is tested.

2. Principle of MHD Separation Method

Figure 1 shows the principle of the MHD method of separating oil from oil-contaminated seawater based on electromagnetic force. In this method, oil droplets mixed with seawater are assumed to be spherical particles with insulation. When a magnetic field B from a superconducting magnet is applied in the direction (U direction) of seawater flow, the electric current I is generated perpendicular to the magnetic field using electrodes (width W and length L). Then, seawater is subjected to the electromagnetic force F_{MHD} in the direction shown in Fig.1. In contrast, the

Fig. 1 Principle of MHD separation method.

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simulation particles are not subjected to F_{MHD} , but to the separation force F_{Se} , which is similar to buoyancy, in the reverse direction (v direction) of F_{MHD} ; the simulation particles are separated into side A. The separation ratio (the mass of the particles / the total mass of the particles) is 1 for perfect separation, and 0.5 for no separation.

3. Observation of Inside of MHD Separation Cell

Two types of MHD separation cell were used for observation. These separation cells have a different effective length of the electrodes L_E ; $L_E = 30$ mm for cell 1 and $L_E = 50$ mm for cell 2. The electrodes were made of aluminum, 20 mm wide, the distance between the electrodes was 20 mm. The separation cells were made of transparent polyvinyl chloride (PVC), 20 mm wide, 20 mm high, and 290 mm long. The cells installed in the warm bore (horizontal direction; U direction) of a superconducting magnet were observed through optical windows from the side direction (v direction).

Figure 2 shows the schematic diagram of the observation system. The observation system consisted of a separation cell, a split-type superconducting magnet (OXFORD, RHE-1012T-SP), a high-speed video camera (WEINBERGER, SPEEDCAM512), a telescope, a light, and a mirror. The observation experiment was carried out using a NaCl aqueous solution (specific gravity 1.030) instead of seawater and simulation particles (polystyrene particles: 1 mm in diameter and specific gravity approximately 1) instead of oil droplets. The behavior of the

Fig. 2 Schematic of observation system.

Fig. 3 Photograph of separation cell 1 with $I = 10$ mA and $B = 10$ T.

particles was observed under the condition that the sample solution is stopped, the electric current I is 10 mA, and the magnetic field B is 10 T.

As an example of the observation results, a photograph of the separation cell 1 (20 mm $\times$ 20 mm) with $I = 10$ mA and $B = 10$ T is shown in Figure 3. Since the separation force F_{Se} is applied to this side of the photograph, the motion of the particles through this direction is expected. However, the motion in the right and left directions was observed near the edge of the electrodes. The occurrence of vortices was confirmed there. The observation results can be summarized as follows: (1) The mean speeds of the particles in the right and left directions were about 50 mm/s (maximum value) for cell 1 and about 20 mm/s (maximum value) for cell 2; the mean speed of cell 2, which has a large effective length of electrodes was less than that of cell 1, which has a small one near the edge of the electrodes. (2) When electric current is generated downward, clusters of particles were observed due to the adhesion between the particles and the bubbles (Hydrogen gas) generated on the cathode at the lower part of the cell. The occurrence of vortices near the edge of the electrodes is believed to be caused by seawater flow due to the pressure difference caused by the difference in electromagnetic force between the inside cell and the outside cell.

4. Experimental Apparatus for MHD Separation

Figure 4 shows a schematic of the improved MHD separation device. The effective length of the electrodes L_E of this device is 50 mm (the length of the electrodes L is 60

Fig. 4 Schematic of improved MHD separation device.

Fig. 5 Schematic of experimental MHD separation setup.

mm) and larger than that of the previous electrodes [2]. As the effective cross-sectional area of the improved device against electromagnetic force increases in comparison with that of the previous device, vortices hardly occur in the improved device due to the low pressure difference. The width of electrodes is 17 mm and the distance between electrodes is 16 mm; these values are less than that of the separation cells for observation, and depend on the thickness of PVC required to strengthen the cells. Figure 5 shows the schematic diagram of the experimental MHD separation setup. Figures 6 and 7 show photographs of the experimental apparatus. The experimental apparatus consists of the MHD separation device, the split-type superconducting magnet in the cryostat, a seawater tank, a drain tank, a seawater and particle tank, and flow lines.

5. Experiment of Separation and Recovery

At the start of the experiment procedure, the sample solution was made to flow through the separation device at a rate of approximately 1.5 L/min. Next, a mixture of the sample solution and simulation particles (mixing ratio 10:1) in the tank was infused into the separation device. When the electric current was varied from 0 to 0.5 A at the magnetic field B of up to 10 T, the amount of outflowing mixture was measured on both sides A and B; the separation ratio Se defined by

$$Se = \frac{M_A}{M_A + M_B} \quad (1)$$

was analyzed carefully. Here, M_A is the mass of simulation particles in outflowing mixture on side A and M_B is the mass of simulation particles in the outflowing mixture on side B.

Figure 8 depicts the relationship between separation ratio and electric current at a magnetic field of 10 T. Here, the direction of electric current was downward, the same as

Fig. 6 Photograph of experimental apparatus (1).

Fig. 7 Photograph of experimental apparatus (2).

in our previous experiment [2]. As shown in this figure, the separation ratio reached approximately 1 when the electric current was 0.2 A; this separation ratio was larger than the previous values (0.9). This is explained as an effect of the large effective length of the electrodes. In contrast at an electric current of 0.4 A or higher, the separation ratio decreased to almost zero. This is believed to be caused by the blockage of the particle clusters as affected by the bubbles.

The results for an upward electric current are shown in Figure 9. In this case, the separation ratio reached 1, which means perfect separation, when the electric current was 0.1

A or higher. It follows that the formation of particle clusters was suppressed by the nonadhesion between the particles and the bubbles generated on the cathode. For an upward electric current, perfect separation was obtained even at a magnetic field of 5 T, when the electric current was varied from 0.1 A to 0.4 A (Figure 10). The effects of a large effective length of electrodes and an upward electric current on the separation ratio were confirmed.

The separation ratio of oil was closely related with various physical quantities: seawater velocity, magnetic field, electric current density and so on [2]. A percentage and viscosity of oil must be also discussed adequately. A

Fig. 8 Relationship between separation ratio and electric current (downward) at $B = 10$ T.

Fig. 10 Relationship between separation ratio and electric current (upward) at $B = 5$ T.

Fig. 9 Relationship between separation ratio and electric current (upward) at $B = 10$ T.

preliminary experiment of separation and recovery for salad oil was done; the separation ratio was approximately 0.8 with $B = 10$ T and $I = 0.4$ A. The experiments for heavy oil and crude oil are in preparation.

6. Summary

The inside of MHD separation cells was observed successfully using a high-speed video camera. As observation results, it was found that occurrence of vortexes near the edge of the electrodes is caused by seawater flow due to the pressure difference caused by the difference in electromagnetic force between the inside cell and the outside cell. In addition, particle clusters were observed due to the adhesion between the particles and the bubbles generated on the cathode.

The MHD separation device was improved on the basis of the observation results; the effective length of the

electrodes of this device was made longer than that of the previous length to suppress vortexes as much as possible. Using a mixture of artificial seawater and simulation particles, experiments on separation and recovery was carried out. As a result of the experiment, it becomes evident that the separation ratio reached 1, which means perfect separation, even when the upward electric current is 0.1 A and the magnetic field is 5 T. Separation ratio markedly increased in comparison with that in our previous experiment. It follows that the large effective length of the electrodes and upward electric current are effective in improving the characteristics of the MHD separation device. In near future, the MHD separation method will be practically applied to the treatment of oil-contaminated seawater and the effectiveness of this method will be clarified.

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References

- [1] "Sea and Marine Contamination", Matsunaga, K. *et al.*, (2002), Sankyo, in Japanese.
- [2] "Basic Study on Oil Separation from Oil-Contaminated Seawater by MHD Method", Nishigaki, K., Takeda, M., Tomomori, N., Iwata, A., TEION KOGAKU (J. Cryo. Soc. Jpn), Vol.37, No.7, pp343-349, (2002) in Japanese.
- [3] "Flow Control of Seawater With a Diverging Duct by MHD Separation Method", Takeda, M., Tomomori, N., Akazawa, T., Nishigaki, K., Iwata, A., IEEE Trans. Appl. Supercond., Vol.14,

No.2, pp1543-1546, (2004)

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