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(Citation)
IEEE transactions on applied superconductivity,14(2):1543-1546

(Issue Date)
2004-06

(Resource Type)
journal article

(Version)
Version of Record

(URL)
https://hdl.handle.net/20.500.14094/90000222

# Flow Control of Seawater With a Diverging Duct by MHD Separation Method

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***Abstract*—A unique control method for a diverging seawater flow based on electromagnetic force, the so-called MHD (magnetohydrodynamics) separation method, is performed. The experimental apparatus is composed of a 10-T class superconducting magnet, a separation cell, a seawater tank, and a flow system. The constructed separation cell contains parallel electrodes, 18 mm wide, 40 mm long and 20 mm apart, and a diverging duct divided into equal parts, A (not affected by electromagnetic force) and B (affected by electromagnetic force). The dependence of flow ratio (mass of side-A sample solution/total mass of sample solution) on electric current, magnetic field, NaCl concentration and sample velocity has been studied experimentally using NaCl aqueous solution. The possibility of flow control of seawater with a diverging duct by the MHD separation method as well as experimental results are discussed.**

***Index Terms*—Flow control, magnetic separation, MHD method, seawater.**

## I. Introduction

Recently, superconducting electromagnetic ships with a helical insulation wall [1] and oil separation from oil-contaminated seawater [2], which take advantage of electromagnetic force, the so-called MHD (magnetohydrodynamics) force, have been studied using high magnetic fields with a superconducting magnet and electric currents through seawater. The MHD separation method is based on the difference of electric conductivity between seawater and oil; the separation force applied to oil as a reaction of the electromagnetic force is used for oil separation. In our work [2], focusing on the relationship between the characteristics of oil separation and electric current, and magnetic field and seawater velocity, experimental and computational studies on the characteristics have been performed in the case of enlarging a separation cell and particles when high polymer particles were used instead of oil.

In the experiment on oil separation, it becomes evident that the flow ratio of the amount of outflowing seawater at a diverging duct (ratio of the amount of outflowing seawater at side A not affected by electromagnetic force to the total amount of outflowing seawater) changed unexpectedly. In order to understand the characteristics of oil separation by the MHD method, it is important to elucidate the cause for this change of the flow ratio.

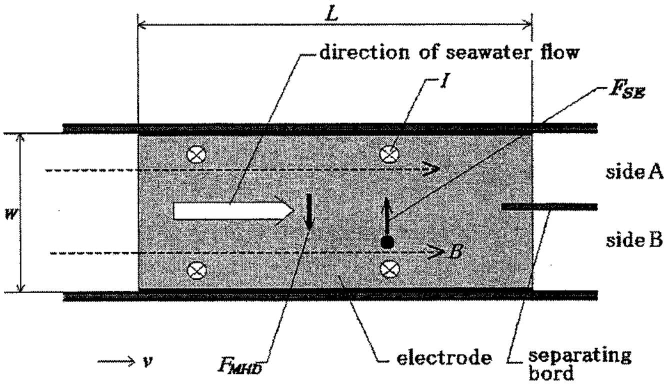


Fig. 1. Principle of MHD separation method.

In this paper, experimental studies on the dependence of the flow ratio on electric current, magnetic field, NaCl concentration and seawater velocity by the MHD method using artificial seawater (NaCl aqueous solution) are reported. In addition, the possibility of flow control of seawater with a diverging duct by the MHD separation method is discussed.

## II. Principle of MHD Separation Method

Fig. 1 shows the principle of the MHD method of oil separation from oil-contaminated seawater based on electromagnetic force. Here oil droplets are assumed to be spherical particles with insulation. As shown in Fig. 1, a magnetic field $B$ is applied in the direction of seawater flow (velocity $v$) and electric current $I$ is generated perpendicular to the magnetic field using electrodes (wide $W$ and length $L$). Then, the seawater is subject to electromagnetic force, $F_{\mathrm{MHD}}$, according to Fleming's rule. On the contrary, the spherical particles are not subject to $F_{\mathrm{MHD}}$, but are subject to separation force, $F_{\mathrm{SE}}$, which is similar to buoyancy, in the reverse direction of $F_{\mathrm{MHD}}$. Therefore, the spherical particles are separated into side A; the MHD separation method is based on the difference in direction between $F_{\mathrm{MHD}}$ and $F_{\mathrm{SE}}$.

## III. Experimental Apparatus and Methods

### A. Separation Cell

Fig. 2 shows the schematic diagram of the separation cell. This cell consists of a diverging duct made of polyvinyl chloride (PVC), a 1-mm-thick separation board made of PVC and 10-$\mu$m-thick Pt-coated Ti electrodes 1 mm thick, 18 mm wide and 40 mm long. The distance between the electrodes is 20 mm.

Manuscript received October 21, 2003. This work was supported in part by a Grant-in-Aid for Exploratory Research from the Japan Society for the Promotion of Science.

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Digital Object Identifier 10.1109/TASC.2004.830697

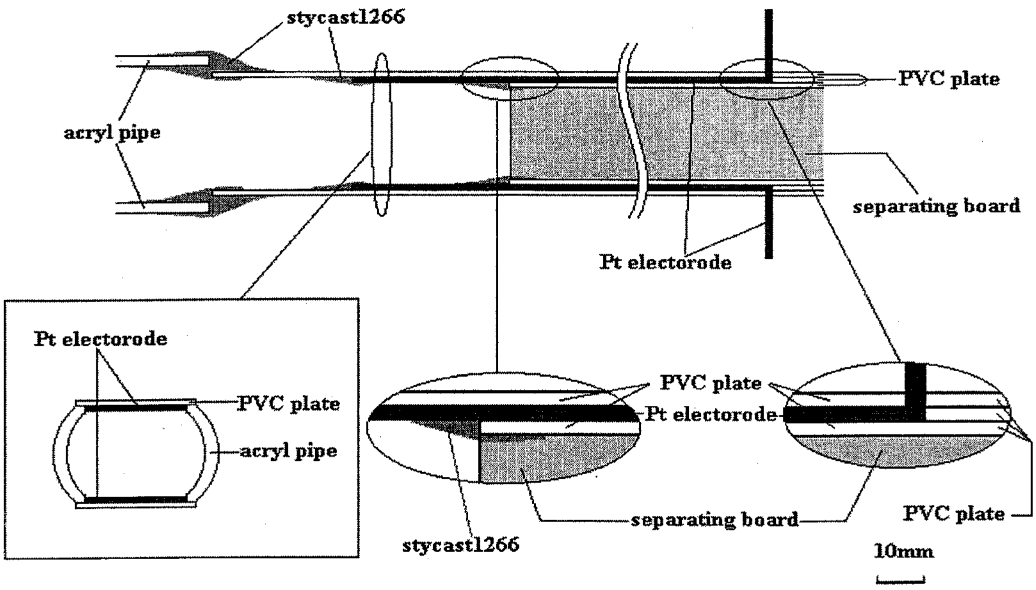


Fig. 2. Separation cell.

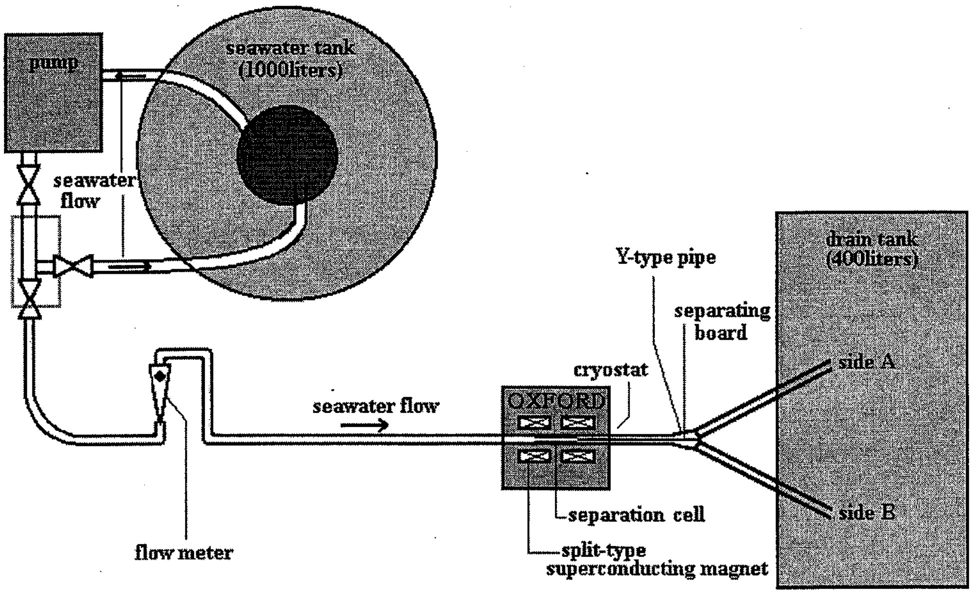


Fig. 3. Schematic diagram of experimental setup.

The diverging duct was divided into equal parts A (not affected by electromagnetic force) and B (affected by electromagnetic force).

### B. Experimental Setup

Fig. 3 represents the schematic diagram of the experimental setup. The experimental apparatus consists of a split-type superconducting magnet (Oxford Instrument), a separation cell, a Y-type pipe, a seawater tank, a drain tank, a pump, a flow meter and a flow line. The maximum field of the magnet is 10 T with a warm bore of 34 mm diameter and 240 mm length. The magnetic field was nearly uniform within $\pm 20$ mm of the center of the magnet and the homogeneity remained within $\pm 2\%$ [3]. The capacity of the seawater tank and the drain tank are 1000 L and 400 L, respectively. The total length of the flow line is 8 m.

### C. Experimental Method

The flow experiment was carried out using a NaCl aqueous solution instead of seawater without spherical particles; the amount of outflowing NaCl solution was measured during 1 minute at both sides A and B in terms of electric current $I$ (0–1 A), magnetic field $B$ (0–10 T), NaCl concentration $c$ (3.5–10%) and sample velocity $v$ (1.5–6 cm/s). At the beginning of the experimental procedure, the sample solution ($c = 3.5\%$) was made to flow through the separation cell at the rate of approximately 1 L/min ($v = 3$ cm/s). Next, when the electric current $I$ was generated within the range of 1 A in the magnetic field $B$ of up to 10 T, measurements of the amount of outflowing sample solution were carried out; the flow ratio $Q$ defined by the following equation was analyzed carefully:

$$Q = \frac{m_A}{m_A + m_B}. \tag{1}$$

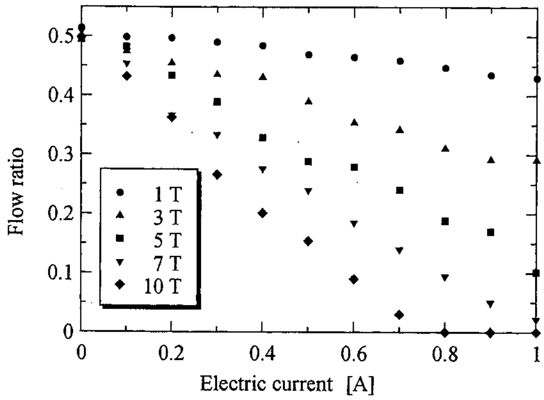


Fig. 4. Electric current-dependence of flow ratio as a parameter of magnetic field ($c$ = 3.5%, $v$ = 3 cm/s).

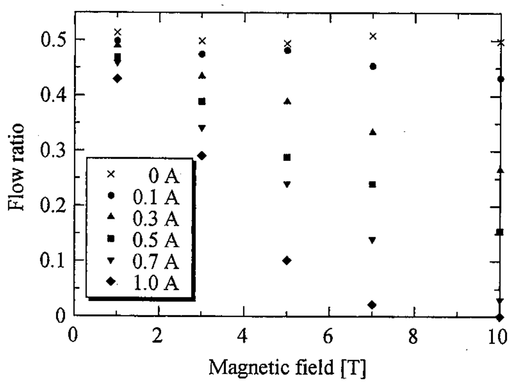


Fig. 5. Magnetic field-dependence of flow ratio as a parameter of electric current ($c$ = 3.5%, $v$ = 3 cm/s).

Here, $m_A$ is the mass of outflowing sample solution at side A and $m_B$ is the mass of outflowing sample solution at side B. In the case of zero electromagnetic force, $Q = 0.5$ because of equal outflow at both sides of the diverging duct. When all sample solution flowed out at side B due to strong electromagnetic force, on the other hand, $Q = 0$.

## IV. Experimental Results and Discussion

### *A. Dependence of Flow Ratio on Electric Current and Magnetic Field*

Fig. 4 shows the relationship between flow ratio and electric current as a parameter of magnetic field with $c$ = 3.5% and $v$ = 3 cm/s. Experimental values are the averages of three data values. As shown in Fig. 4, the flow ratio decreased linearly with increasing electric current in a constant magnetic field. In addition, the flow ratio was zero in the case that magnetic field/electric current were 7 T/1 A and 10 T/0.8 A, or more; the outflow of sample solution at side A was stopped completely.

Fig. 5 represents the relationship between flow ratio and magnetic field as a parameter of electric current with $c$ = 3.5% and $v$ = 3 cm/s. As seen in this figure, the flow ratio decreased linearly with increasing magnetic field in a constant electric current. The reason why the flow ratio is proportional to electric current and magnetic field may be explained from the fact that electromagnetic force applied to the sample solution increases with electric current and magnetic field, and the flow ratio is affected directly by this force.

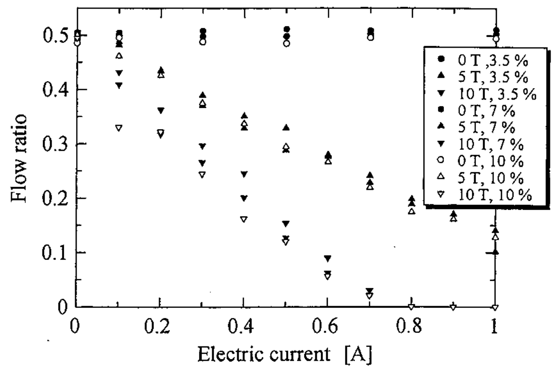


Fig. 6. Electric current-dependence of flow ratio as parameters of magnetic field and NaCl concentration ($v$ = 3 cm/s).

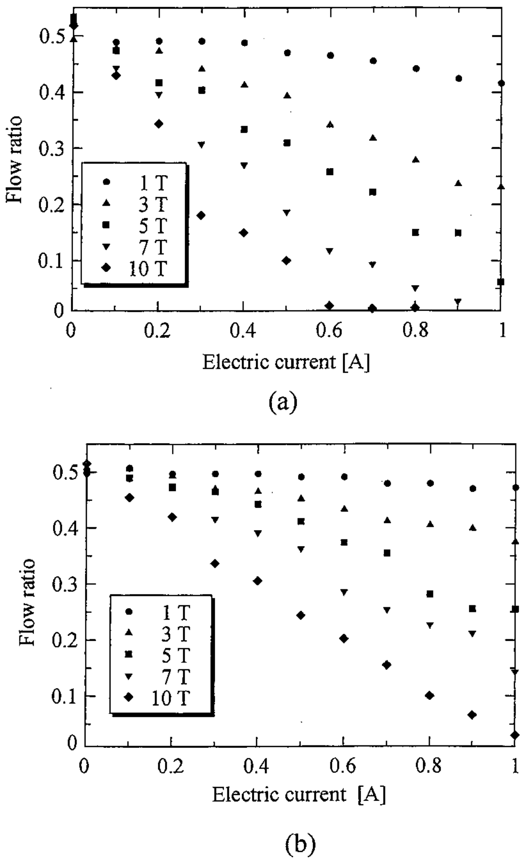


Fig. 7. Electric current-dependence of flow ratio as a parameter of magnetic field ($c$ = 3.5%). (a) $v$ = 1.5 cm/s; (b) $v$ = 6 cm/s.

On the condition of controlling electric current in the experiment, the flow ratio under the constant electric current should not be changed due to the constant electromagnetic force in spite of varying the NaCl concentration, i.e., the electric conductivity. Indeed, the relationship between flow ratio and electric current was independent of NaCl concentration, as shown in Fig. 6.

### *B. Dependence of Flow Ratio on Sample Velocity*

Figs. 7(a) and 7(b) show the relationship between flow ratio and electric current as a parameter of magnetic field with $c$ = 3.5%, $v$ = 1.5 cm/s and $v$ = 6 cm/s. When $v$ = 1.5 cm/s, as shown in Fig. 7(a), the flow ratio was zero in the case that magnetic field/electric current were 7 T/0.9 A and 10 T/0.6 A, or more. When the sample velocity $v$ increased to $v = 6\ \mathrm{cm/s}$, as shown in Fig. 7(b), the flow ratio was zero in the case of 10 T/1 A or more. In addition, the decline in the flow ratio to electric current decreased with increasing sample velocity. This is caused by a relatively fast flow before separation at the separating board when sample velocity increases.

We consider the possibility of flow control of seawater with a diverging duct by the MHD separation method as follows: The characteristics of the MHD separation method are (1) the treatment of a small amount of flowing seawater at the rate of the order of 1 L/min, (2) the flow ratio is dependent on electric current, magnetic field and sample velocity, but independent of NaCl concentration, and (3) the flow ratio can be controlled by varying the values of electric current in a constant magnetic field and at a constant sample velocity. It follows that the flow control of seawater with a diverging duct by the MHD separation method is applicable for small amounts of flowing seawater.

## V. Summary

Our results can be summarized as follows.

1) Using NaCl aqueous solution, the dependence of the flow ratio on electric current (0–1 A), magnetic field (0–10 T), NaCl concentration (3.5–10%) and sample velocity (1.5–6 cm/s) has been studied experimentally by means of the MHD separation method.
2) The flow ratio is dependent on electric current, magnetic field and sample velocity, but independent of NaCl concentration.
3) The flow control of seawater with a diverging duct by the MHD separation method is applicable for small amounts of seawater flowing at the rate of the order of 1 L/min.

## References


[1] K. Nishigaki, C. Sha, M. Takeda, Y. Peng, K. Zhou, A. Yang, D. Suyama, Q. J. Qing, L. Yan, T. Kiyoshi, and H. Wada, "Elementary study on superconducting electromagnetic ships with helical insulation wall," *Cryogenics*, vol. 40, no. 10, pp. 353–359, 2000.

[2] K. Nishigaki, M. Takeda, N. Tomomori, and A. Iwata, "Basic study on oil separation from oil-contaminated seawater by MHD method" (in Japanese), *Teionkougaku*, vol. 37, no. 7, pp. 343–349, 2001.

[3] S.-H. Lee, M. Takeda, and K. Nishigaki, "Influence of NaCl concentration on the gas-liquid interface deformation of water in magnetic fields," *Jpn. J. Appl. Phys.*, pt. 1, vol. 40, no. 10, pp. 6171–6176, 2001.