Fundamental Study of Helical-Type Seawater MHD Power Generation with Partitioned Electrodes

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As an application of superconducting technology to the field of maritime sciences, the authors have studied a seawater magnetohydrodynamics (MHD) power generator/hydrogen generator using a high-field superconducting magnet, focusing on natural marine energy. The seawater MHD power generator is a unique system that not only transforms the kinetic energy of ocean and tidal currents directly into electric energy but also generates hydrogen gas in accordance with the law of electromagnetic induction. Recently, a new helical-type seawater MHD generator with partitioned electrodes having a helical insulation wall with an outer diameter of 97 mm and a length of 155 mm and a 7 T solenoid superconducting magnet has been designed, fabricated and examined to elucidate the relationship between the characteristics of the generator and helical flow. It was found that the electromotive force obtained was in agreement with the calculated value in stable helical flow and was independent of the direction of the induced electric field.

1. Introduction

A seawater magnetohydrodynamics (MHD) power generator/hydrogen generator is a unique system that not only transforms the kinetic energy of ocean and tidal currents directly into electric energy but also generates hydrogen gas as a by-product, which is expected to be used as an ultimate clean energy source. In addition, the seawater MHD generator has the advantages of no mechanical parts and being maintenance-free as well as low loss and high efficiency in comparison with a conventional seawater turbine [1]. In seawater MHD generation, a new helical-type seawater MHD power generator using a solenoid superconducting magnet is an attractive renewable energy source that can be installed offshore [2-7]. So far, the experimental values of the electromotive force and output of the generator have been smaller than the calculated values [2, 4, 6]. The main cause of this difference was considered to be due to unstable helical flow inside the generator. Then, measurements of the velocity distribution inside the generator using a five-hole pitot tube were carried out to clarify the cause [7].

From the experimental results, unstable helical flow in the vicinity of the entrance and stable helical flow in the vicinity of the middle of the generator were concluded. However, the relationship between the characteristics of power generator and the helical flow has not yet been studied. The purpose of the present work is to elucidate the relationship between the electromotive force and the helical flow as well as the influence of the direction of the induced electric field on the electromotive force, using a helical-type seawater MHD power generator with partitioned electrodes. In the case that the electromotive force is independent of the direction of the induced electric field, the helical-type generator with a permanent magnetic field works at both ebb and flood tide, showing similar characteristics.

2. Principle of Helical-Type MHD Generator

Figure 1 shows the principle of the helical-type seawater MHD power generator. This generator consists of double-cylindrical coaxial electrodes, a helical insulation wall and a solenoid superconducting magnet. Seawater flow is changed from axial flow to rotational flow/helical flow around an inner electrode by the helical wall.

When seawater rotates around the inner electrode in a magnetic field $B$ parallel to the coaxial direction, an electromotive force

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is generated according to the law of electromagnetic induction. The electromotive force \( V_e \) is expressed using eq. (1) on the assumption that the average flow velocity in the generator is \( U_{av} = r \omega \), where \( r \) is the rotational radius and \( \omega \) is the angular velocity:

\[
V_e = \frac{nU_{av} \pi (r_2^2 - r_1^2)}{l_{hc}}.
\]  

(1)

Here, \( n \) is the rotation number, \( r_2 \) is the inner radius of the outer electrodes, \( r_1 \) is the outer radius of the inner electrode and \( l_{hc} \) is the central length of the helical flow. Owing to the configuration of the solenoid magnet, the helical-type generator has two directions of the induced electric field: a forward and a reverse electric field.

An electric current \( I \) is generated when \( V_e \) is higher than the electrolysis voltage \( V_{el} \); an electric power \( P \) is generated owing to an electric current with external load \( R_{ex} \). In the case of \( R_{ex} = R_{in} \), where \( R_{in} \) is the internal load (the resistance of seawater), the maximum electric power \( P_{max} \) can be obtained as

\[
P_{max} = \frac{1}{4R_{in}} (V_e - V_{el})^2.
\]  

(2)

3. Experimental Apparatus

Figure 2 shows a photo of the outer electrodes with insulation rings and a helical wall. These electrodes were made of SUS 316 stainless steel and numbered from 1 to 4 along the flow direction; electrode 1 corresponds to the first turn of the helical wall and electrode 4 corresponds to the fourth turn of the helical wall. The helical wall, which has an outer diameter of 97 mm, a length of 155 mm, a pitch length of 37.5 mm and a rotation number of 4, was made of Stycast 1266J on the basis of calculation of the optimal \( P_{max} \).

A schematic diagram of the experimental setup is shown in Figure 3. The experimental system consists of a generator with a 7 T solenoid superconducting magnet, a seawater tank (1 m³), a circulation pump (CMP6-63.7, Terada Pump Co., Ltd.), a flowmeter (UZG-VTS2-L, Nippon Flow Cell, Co., Ltd.), a differential pressure gauge (DD101K for 100 kPa, JTEKT Corp.), a data processing system (FE-300, DEICY Corp.) and a PC. In the experiment, artificial seawater (NaCl aqueous solution) with an electric conductivity of 5 S/m was used, and only maximum magnetic field of 7 T was applied because the electromotive force was proportional to the magnetic field [2, 4, 6].

4. Experimental Results and Discussion

4.1 Experiment of Flow Loss

The superconducting magnet used has a vertical experimental space at room temperature because of the configuration of the cryostat. Before carrying out an experiment on the characteristics of the generator, an experiment on the flow loss of the generator was performed to compare the cases of vertical and horizontal settings.
Figure 4 shows the experimental result for the relationship between the flow loss/head and the average flow velocity in the cases of vertical and horizontal settings. The average flow velocity was estimated as the amount of seawater flow divided by the cross section of the helical flow. As shown in Fig. 4, the head for the vertical setting was in agreement with the head for the horizontal setting added to the potential head between the pressure taps of 20 cm. Accordingly, the vertical setting of the generator was considered acceptable.

4.2 Experiment on Voltage-Current Characteristics

An experiment on the voltage-current characteristics of the generator was done to obtain the electrolysis voltage $V_{re}$ and internal load $R_{in}$. Figure 5 shows electrolysis curves for the partitioned electrodes, which correspond to the sequence of turns, in a flow of 10 m$^3$/h (2.2 m/s) and a forward electric field, where the outer electrode is charged higher than the inner electrode. We obtained $V_{re} = 1.7$ V and $R_{in} = 4.0$ $\Omega$ for the first turn, $V_{re} = 1.7$ V and $R_{in} = 3.4$ $\Omega$ for the second turn, $V_{re} = 1.7$ V and $R_{in} = 5.4$ $\Omega$ for the third turn and $V_{re} = 1.5$ V and $R_{in} = 3.80$ $\Omega$ for the fourth turn. The values of $V_{re}$ were larger than the theoretical value (1.36 V), and the values of $R_{in}$ were about 8-9 times larger than the theoretical value.

4.3 Experiment on Electromotive Force

To confirm the influence of the direction of the induced electric field, which corresponds to the direction of the magnetic field,
on the electromotive force $V_e$ and to confirm the difference in $V_e$ among the partitioned electrodes, $V_e$ was measured as a function of flow velocity in a magnetic field of 7 T using NaCl aqueous solution. In the experiment, the forward magnetic field was defined as the upward magnetic field, where the outer electrodes were charged higher than the inner electrodes, while the reverse magnetic field was defined as the downward magnetic field, where the inner electrodes were charged higher than the outer electrodes. For every measurement, each electrode was first short-circuited by switching on a shunt for 30 s, then $V_e$ was measured after a waiting time of 30 s. One data point for $V_e$ was obtained from the average value with a sampling rate of 300 Hz and a sampling time of 10 s.

Figure 6 shows the average electromotive force $V_e$ with every short-circuiting in both the forward and reverse magnetic fields obtained in several data acquisitions. In this figure, dashed lines express values calculated using eq. (1). It was found that $V_e$ was independent of the direction of the magnetic field; in other words, $V_e$ was independent of the direction of the induced electric field. In addition, the values of $V_e$ for electrodes 2 and 3 were proportional to the flow velocity for flow velocities of less than 5 m/s, in agreement with eq. (1), and were larger than those for electrodes 1 and 4. This is believed to be caused by the stable helical flow around the middle of the generator and the relatively unstable helical flow near the entrance and exit of the generator. Meanwhile, the values of $V_e$ for electrodes 2 and 3 were not proportional to the flow velocity for flow velocities of larger than 5 m/s. This is probably caused by a secondary flow along the helical wall.

4.4 Experiment on Generator Output

Figures 7 and 8 show the experimental results for the generator output in the forward and reverse magnetic fields, respectively. As shown in these figures, the generator output was zero at a flow velocity of less than about 4.5 m/s because of the low electromotive force being less than the electrolysis voltage. Meanwhile, the generator outputs of four electrodes in both forward and reverse magnetic field at a flow velocity of larger than 4.5 m/s were scattered considerably. This is thought to be caused by small difference between the electromotive force and the electrolysis voltage. The total generator output exceeded
0.01 W at a flow velocity of 7 m/s. This value was unexpectedly small because of the high internal load and the configuration of the generator. According to performance predictions of the helical-type generator for enlargement on the basis of similar configuration, the total output of the generator having a helical wall with an outer diameter of 2 m exceeds tens kW, which is larger than the cooling power of cryocooler for a superconducting magnet.

5. Summary

A helical-type seawater MHD power generator with partitioned electrodes was designed, fabricated and examined. The generator had four electrodes and a helical wall having an outer diameter of 97 mm, a length of 155 mm, a pitch length of 37.5 mm and a rotation number of 4. Experiments on the flow loss, voltage-current characteristics, electromotive force and output of the generator were carried out using NaCl aqueous solution. It was experimentally found that in a magnetic field of 7 T, the electromotive forces of electrodes 2 and 3 under a stable helical flow were in agreement with the calculated values and were independent of the direction of the induced electric field.

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