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Arc rotation characteristics of a plasma centrifuge with a counter-rotating electrical discharge

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ABSTRACT

Arc rotation velocities of a plasma centrifuge with a counter-rotating electrical discharge were measured by using double probes placed perpendicular to each other. The measurement results were compared with the results calculated from the analytic solutions suggested by Hong et al. The comparison revealed that the arc column near the electrodes can be rotated much faster by increasing the arc currents and magnetic fields. For example, the rotational velocity of the are column near the electrodes was increased from 75 to 150 m/s with the increase of magnetic flux density from 15 to 45 mT at the fixed arc current of 50 A. On the other hand, the rotational velocity of the arc column showed only negligible changes at the plane of symmetry, where the radial component of the arc current was designed to become zero due to the symmetry of the counter-rotating electrical discharge. From these measurement results and analytic solutions, gaseous mixtures of different masses can be separated effectively near the electrode regions of a plasma centrifuge with a counter-rotating electrical discharge.

1. Introduction

As an alternative to the conventional mechanical centrifuges, plasma centrifuges have attracted much attention for the separation of mixed gases with different masses such as isotopes of chemical elements [1–3]. Compared with mechanical centrifuges, a plasma centrifuge has no moving parts except the arc column, which is rotated by the Lorentz force in a stationary discharge chamber. Since the Lorentz force can be amplified by the magnetic field applied on the arc current, extremely high rotational speeds can be achieved in plasma centrifuges without involving of moving parts as in mechanical centrifuges. Consequently, the mass separation of gaseous mixtures or isotopes of chemical elements can be carried out efficiently in a weakly or a strongly ionized arc column [4–6]. In a vacuum arc centrifuge, for example, there are no upper limits in the rotational velocity for strongly ionized plasmas theoretically [7–9]. Accordingly, some metallic isotopes have been separated and enriched efficiently from the strongly ionized plasmas which can be generated by the laser-assisted evaporation of metallic target materials.

For the isotopes of gaseous elements with low mass numbers, however, the weakly ionized plasmas are preferable to the strongly ionized plasmas [6,10,11]. Although a plasma centrifuge with a weakly ionized arc column has a limitation in increasing velocity due to the friction between the ionized gases and the background neutrals in addition to Alfven velocity, it can attain faster rotational velocity than a conventional mechanical centrifuge does. Moreover, with no need for expensive devices, such as lasers and high vacuum systems, a plasma centrifuge with a weakly-ionized arc column can be cost-effective in the separation of gaseous isotopes. In particular, many kinds of analytic solutions for the rotational velocity of a weakly ionized plasma centrifuge have been presented [12–15]; therefore, the performance of a weakly ionized plasma centrifuge can be easily predicted for various types of discharge structures or electrode geometry. Hong et al. [14], for example, suggested analytic solutions for the rotational velocity of the plasma centrifuges with a counter-rotating electrical discharge as functions of the discharge currents and magnetic fields.

Fig. 1 represents Hong et al.'s theoretical model of a weakly ionized plasma centrifuge with a counter-rotating electrical discharge. As described in this figure and the Hong et al.'s paper [14], they assumed that the arc current enters and leaves both the electrodes only through the inner surface of the cathode and anode with vanishing axial width, respectively. In addition, it is also

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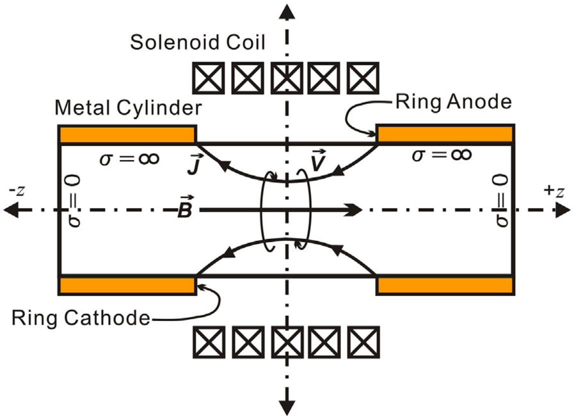

Fig. 1. A theoretical model of a plasma centrifuge with a counter-rotating electrical discharge.

assumed that the magnetic field is uniform along the *z*-axis and the velocity of the arc column has a rotational component only. The derived analytic solutions revealed that the counter-rotating plasma centrifuge has the maximum rotational velocity near both the ring-shaped electrodes while the rotational velocity of the arc column becomes zero at the plane of symmetry due to the configuration of the arc column as illustrated in Fig. 1 [14]. By using these two regions near the ring-shaped electrodes, mass separation can be progressed effectively at high rotational velocities. From these analytic results, they concluded that counter-rotating plasma centrifuges could be more beneficial for isotope separation than other types of electrical discharge, such as, the divergent plasma centrifuge [12] which has one maximum velocity region.

In order to verify these structural advantages of a counter-rotating electrical discharge, we designed a plasma centrifuge with the ring-shaped electrodes as shown in Fig. 1. Neon, composed of 90.48% of ^{20}Ne and 9.25% of ^{22}Ne in natural state, was used as plasma gas and the measurements of the rotational velocity of the arc were carried out using a pair of the electrostatic probes, double Langmuir probe. The measured results were also compared with the results from the analytic solutions for various arc currents, and the differences were discussed to evaluate the practical applications of a plasma centrifuge with the counter-rotating electrical discharge.

2. Experimental setup

Fig. 2 shows the experimental setup for the counter-rotating plasma centrifuge. It consists of a vacuum chamber, water-cooled electrodes, a ceramic (Al_2O_3) tube between electrodes, a solenoid, gas supply system, DC power supply, vacuum pump and measurement system. The vacuum chamber, inserted into a cylindrical solenoid, includes two ring-shaped electrodes facing each other at a distance of 30 mm. And the solenoid is fabricated using an acryl bobbin with an inner diameter of 100 mm and length of 140 mm. The ring shaped electrodes are made of a copper duct with rectangular cross-section (10 mm × 10 mm) in order to secure a coolant conduit inside them. The inner diameter and outer diameter of these electrodes are as 40 mm and 60 mm, respectively. With the same diameters as the electrodes, an alumina tube is placed coaxially for the electrical insulation between the facing surfaces of the electrodes. By introducing this insulating tube, the arc current can be expected to flow from the inner surface of the ring anode to the inner surface of the ring cathode as described in Hong et al.'s analytic model and boundary conditions [14]. In addition, copper wires with a diameter of 1.4 mm were wound on the acryl bobbin of the cylindrical solenoid to produce uniform magnetic fields so that the Lorentz force, a magneto-motive force given by the vector cross product of the arc current density and magnetic flux density, may be driven over the discharge region between the electrodes. Thus, the arc column was designed to be formed under the magnetic fields having only the axial component.

In order to estimate the magnetic flux density and uniformity, a simulation using the well-known Poisson code [16] was carried out for the designed solenoid. Fig. 3 shows the calculated axial component of the magnetic field, B_z, at the coil currents of 3 A along the centerline of the cylindrical solenoid from the center of the two electrodes ($z = 0$ mm) to the end of solenoid ($z = 75$ mm). As shown in this figure, the axial component of the magnetic field has a relatively uniform profile ranging from 42 to 45 mT over the discharge region ($0 < z < 25$ mm), while B_z decreases slightly with the increase of *z*-axis due to the edge effect of solenoid. Fig. 4 illustrates the ratio of the radial component to the axial component of the magnetic field, (B_r/B_z) at the end of the solenoid ($z = 75$ mm) where it is expected that the edge effect becomes larger so that the radial component of the magnetic field grows higher. Although this ratio increases with the increase of the radial positions in Fig. 4, the ratio, B_r/B_z, is within 3.5%. From these simulation results for the designed cylindrical solenoid, it can be justifiably assumed that only the uniform axial component of the magnetic field exists inside the solenoid. And this assumption was also adopted in Hong et al.'s derivation of the analytic solutions. Thus, magnetic field vector can be expressed as $\boldsymbol{B} \sim (0, B_\theta, B_z)$ in this paper, where B_θ indicates the induced magnetic field by arc current. In addition, we adopted the simulation results for the various coil currents as the practical values of B_z for this experiment due to the actual difficulty

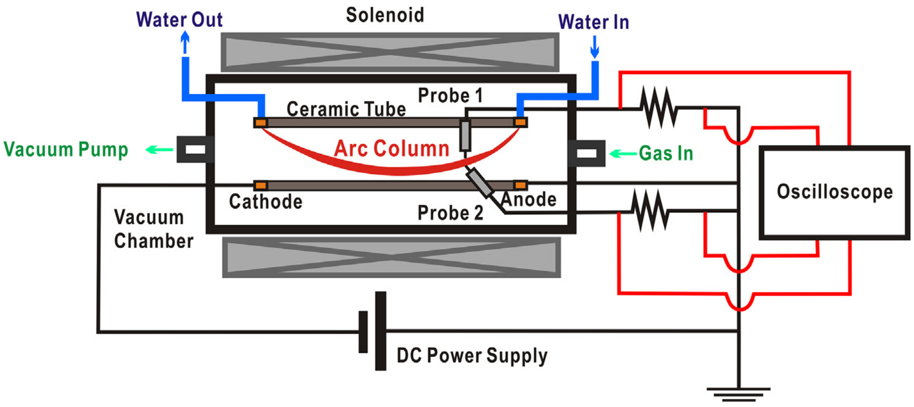

Fig. 2. Experimental setup for the measurement of the rotational velocity of the arc column in the plasma centrifuge with a counter-rotating electrical discharge.