EFFECT OF A MAGNETIC FIELD ON TURBULENCE OF A NON-EQUILIBRIUM PLASMA JET

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ABSTRACT

This paper clarifies experimentally that the enhancement and suppression of turbulence of a non-equilibrium plasma jet is enabled by applying a magnetic field. The power spectra and turbulence intensities of electron and ion saturation currents measured by probe methods, and the fluctuations of a plasma jet are visualized by an infrared themo image processor and a CCD camera.

1. INTRODUCTION

Low pressure non-equilibrium plasma jets have a strong potential for the industrial applications and establishment of the technology to control a plasma flow is highly awaited. The authors have shown in previous papers[1][2] that a magnetic field is very effective for precise control of a plasma jet with clean and stable condition. Those papers also clarified the mechanism to control a plasma jet by distribution of electron temperature, electron density, gas temperature, flow velocity and so forth.

On the other hand, there are some reports intending to clarify the structure of flow and turbulence of plasma jets under no magnetic fields by clarifying states of turbulence. These reports points out the importance of the turbulence's influence by indicating the fact that turbulence is one of the factors to decide the value of characteristics, stability and precise spraying of plasma jets. However, few research are published that studies the structure of low pressure plasma jets' turbulence under magnetic fields though the magnetic control is expected as an effective new method in material processing fields. Clarifying the behavior of turbulence of plasma jets under a magnetic field would give a high potential to industrial applications in higher activation and stabilization of plasma jets.

From those points of view, this paper is intended to clarify experimentally the effect of a magnetic field on a non-equilibrium plasma jet by using probe methods and visualization methods.

2. EXPERIMENTAL SETUPS AND TECHNIQUES

Figure 1 shows the experimental setup. The working gas is argon ionized between a cooled cathode of tungsten rod and a cooled anode nozzle of copper. The typical operating condition of input power for discharge is 22 V and 400 A. The measurement is

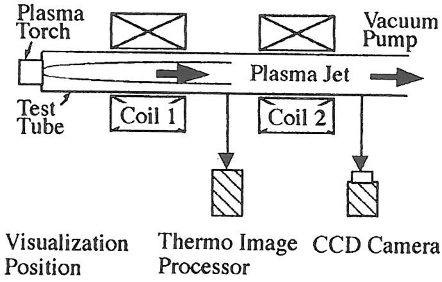

Fig. 1 Experimental setup

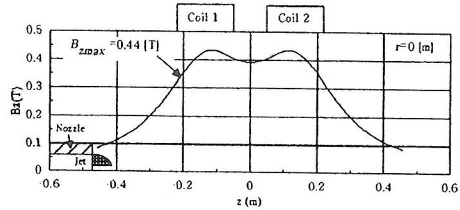

Fig. 2 Axial distribution of magnetic flux density

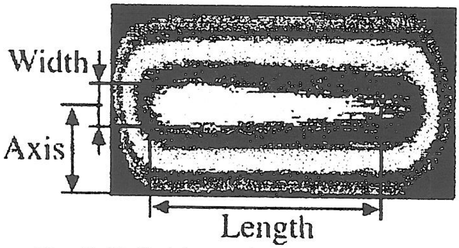

Fig. 3 Definitions of width, length and center axis position

started 15 s after turning the power on. The plasma jet is produced in the straight pipe, 2 m in length and 0.08 m in diameter. The operating pressure in the pipe is from 0.88 kPa to 0.90 kPa at 3.5 g/s of argon mass flow rate.

Figure 2 shows the axial distribution of magnetic flux density. The location of two solenoid coils are also shown in the figure. The central point between the two coils is set as z=0 m, where is 0.473 m downstream from the nozzle exit. The applied magnetic flux density is B_{zmax}=0T and B_{zmax}=0.44T.

The probes used for measuring electron and ion saturation currents are 0.2 mm in diameter and 2.0 mm in length. These two probes were installed 1.5 mm away from each other. One was set parallel to the magnetic line of forces and the other set vertical. Electron and ion saturation currents, which have strong correlations with electron and ion as micro behaviors of a plasma jet, were measured when applying 10V and -10V to probes respectively.

The power spectra of electron and ion saturation currents was observed up to 10 kHz by FFT Analyzer. The turbulence intensity of electron saturation current was calculated by using following formulas:

$$i_{es}'(r) = i_{es}(r) - I_{es}(r) \qquad (3-1)$$

$$\text{Normalized turbulence intensity} = \frac{\sqrt{\overline{i_{is}'(r)^2}}}{I_{is}(r)_{max}} \qquad (3-2)$$

Here, $i_{es}(r)$ is the electron saturation current, $I_{es}(r)$ is time average of $i_{es}(r)$, and $i_{es}'(r)$ is a fluctuating component defined by the formula (3-1). Sampling time is 3.9 ms, and the number of samples is 2560 points. Turbulence intensity of ion saturation current was measured by the same method.

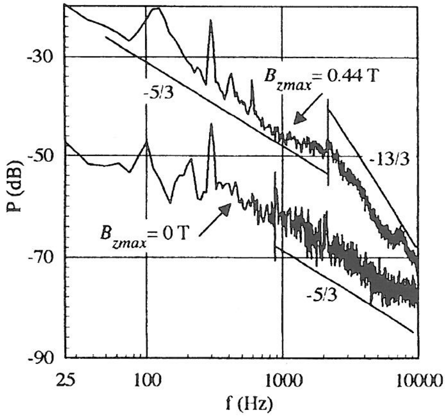

Fig. 4 Power spectra of electron saturation current

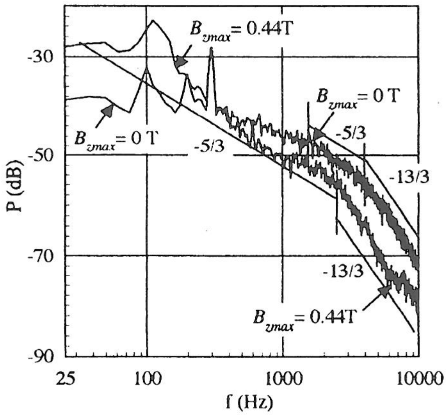

Fig. 5 Power spectra of ion saturation current

Macro behaviors of plasma jet were visualized by the following two methods. First, fluctuation of a plasma jet was taken by CCD camera in both cases with and without magnetic fields. It was taken at the position down stream from the coil 2 where is near the end of the jet as shown in figure 1.

The second one was visualized by infrared thermo image processor whose sampling wavelength is 1 μm. Figure 3 shows the detailed definitions of width, length and center axis position of the high temperature region of excited atoms of a plasma jet. The magnitudes of their fluctuations were calculated by the same method of electron turblence intensity from 60 continuous photographs are taken with 1/30 s sampling time.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3-1. Characteristics of micro behavior

Figure 4 shows the power spectra of electron saturation current at z=0 m on the center axis. The law of -5/3 power, which means turbulent diffusion occurs, exists in the area from the low frequency of about 100 Hz to 2 kHz under a magnetic field. In the high frequency area of over 2 kHz, the law shifts to that of -13/3 power, which means ambipolar diffusion exists[3]. On the other hand, under no magnetic fields, the law of -5/3 power exists only in the area of over 1 kHz. The power level increases rapidly in all area under a magnetic field. These may result from an increase of electron density caused by restraint of electron by magnetic force lines and an increase of electron temperature by suppression of heat diffusion and by joule heating. Thus, both of the laws of -5/3 power and -13/3 power appear in the area of wide frequency under a magnetic field.

Figure 5 shows the power spectra of ion saturation current at z=0 m on the center axis. The power spectrum of ion saturation current is different from the case of electron saturation current as it does not show a large change no matter whether with or without magnetic fields. However, under a magnetic field, the power spectrum of ion saturation current shows about the same decreasing process as the spectrum of electron saturation current. This implies that the diffusion process is the same under a magnetic field

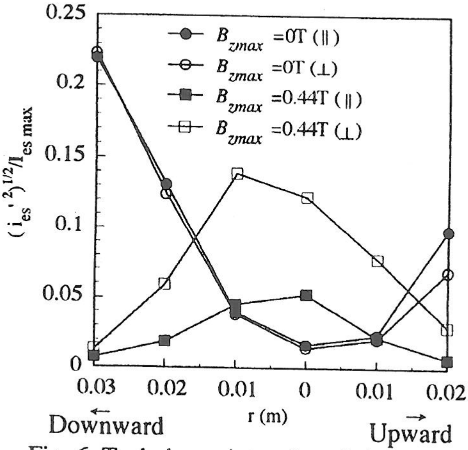

Fig. 6 Turbulence intensity of electron saturation current

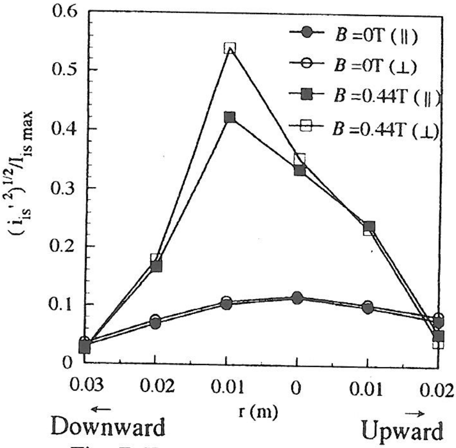

Fig. 7 Turbulence intensity of ion saturation current

between electron and ion, while it is different under no magnetic fields. It can be result from that ambipolar diffusion by coulomb force between electron and ion gets stronger in the axial direction.

Figure 6 shows the radial distributions of the turbulence intensity of electron saturation current at z=0 m. The subscripts ∥ and ⊥ mean that the measurement was done with a probe horizontal to the magnetic force lines and another vertical respectively. Without magnetic fields turbulence intensity marks the minimum about 0.02 around r=0 m and increases in the vicinity of the pipe wall. This phenomena coincides with the distribution of turbulence intensity of electron density by Tikhomirnov[4]. Under a magnetic field the turbulence intensity marks the maximum around the center of the jet and decreases as getting closer to the pipe wall. These may be caused by an increase of the number of injecting electron to the probe, which means that electron moves in a circular path and electron density increases, in the center region of a plasma jet and also by an increase of heat energy by cyclotron resonance. In addition the fact that the turbulence intensity changes by about 3 times dependent on the direction of the probe suggests anisotropy of electron turbulences.

Figure 7 shows the radial distributions of turbulence intensity of ion saturation current. Without magnetic fields the turbulence intensity is small. This is largely different from the case of electron saturation current. This radial distribution is similar to the distribution of turbulence intensity of neutral particles measured by Spores[5]. This suggests that ions behave as neutral particles rather than charged particles under no magnetic fields. Under a magnetic field the turbulence intensity increases rapidly and gets the maximum in the center region of the plasma jet and decreases as getting toward the pipe wall. This may be considered to cause an increase of gas velocity and gas temperature in the center region, and the increase makes larger gradient of the velocity and the temperature in radial direction. Increased shearing stress and heat flux in radial direction[6] and convection would be converted into turbulence energy. Other possible reason are a large Lamor radius of 1×10^{-3} order and rapid increase of collision frequency with increased number density of electron.

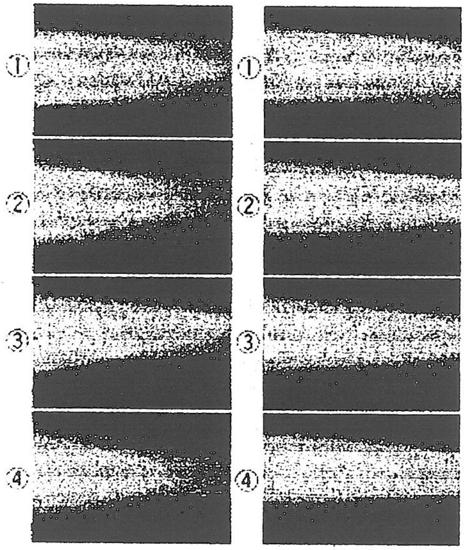

Fig. 8 Continuous photographs of fluctuations of a plasma jet

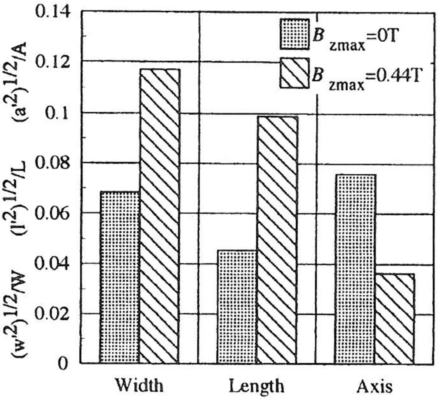

Fig. 9 Magnitudes of fluctuations of width, length, center axis position of high temperature region measured by infrared thermo image processor

3-2. Characteristics of macro behavior

Figure 8 is continuous photographs of fluctuations of a plasma jet observed in the down flow from coil 2 by 1/30 second interval. Under no magnetic fields the fluctuation is large. On the other hand, it is obvious that the fluctuation under a magnetic field is small and stabilized. This result implies that exited heavy particles which are the radiation source is stabilized by applying a magnetic field.

Figure 9 shows the magnitudes of fluctuations of the high temperature regions of a plasma jet measured by infrared thermo image processor between coil 1 and 2. The detailed width, length and center axis position is indicated on the figure 3. The magnitudes of the width and length of the high temperature region become about double under a magnetic field. The magnitude of the fluctuation of the center axis position in the high temperature region becomes about half under a magnetic field. These tendencies that the magnitudes of the fluctuations in the center region are increased and a plasma jet is stabilized correspond to the results of probe methods and figure 8 respectively.

These may result from the increase of the turbulence intensity of electron saturation current and of ion saturation current, and the increase of the temperature ion and heavy particles. On the other hand, plasma jets is restrained by radial direction Lorenz force and the diffusion of electron and ion are suppressed toward the pipe wall. Thus, the plasma jet is stabilized under a magnetic field.

4. CONCLUSION

This paper clarified experimentally that the influence of a magnetic field on the turbulence of a non-equilibrium plasma jet in a pipe through micro behavior of electron and ion saturation currents measured by probe methods and the macro behavior by

visualization methods. The main results are summarized as follows:
(1) Under a magnetic field, power level of electron saturation current increases rapidly and its power spectrum is similar to the spectrum of ion saturation current. The turbulence intensity of electron saturation current and ion saturation current increases rapidly in the center region of a plasma jet.
(2) Visualization of the high temperature region of the center area of a jet clarified that the fluctuation of the center axis position is stabilized under a magnetic field though the fluctuation of plasma jets increases in the center region.
(3) These results suggest a possibility to enhance and suppress the turbulence of a plasma jet by a magnetic field. Activation of the turbulence advances the excitation of neutral particles and contributes to functional enhancement of a plasma jet. Suppressing the fluctuation of the center axis position of a jet stabilizes the jet and enables higher quality of plasma spraying. All these indicates controlling the turbulence by a magnetic field is effective method to enhance accuracy, uniformity and stability in the plasma processing.

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