Control of Plasma Jet Using Strong Magnetic Field

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A fundamental study of functional enhancement of plasma jet with external magnetic field was carried out to utilize the attractive properties effectively. The magnetic field was applied to the jet in a vacuum chamber by using a pair of superconducting coils. The behavior of the jet between two coils was taken by a digital camera through the window for observation. The image analysis shows that the jet is constricted radially by the strong magnetic field. However, high brightness region around the center of the jet increases with the field strength. Measurement on the emission was also performed at lateral positions from the center to the outer edge of the jet. The results of emission measurement also supported the constriction of the jet illustrated by the image analysis. It is clarified from these results that the plasma jet can be controlled significantly by using the strong magnetic field.

Key Words: Plasma, Jet, Axisymmetric Flow, Flow Control, Functional Fluid, Magnetic Field, Image Analysis

1. Introduction

Recently, great attention has come to be focused on industrial applications of plasmas because of their attractive characteristics as high enthalpy flow(1). A plasma is also a typical functional fluid in the magnetic field(2). It is, therefore, possible to control the flow characteristics by using magnetic field. The engineering applications will be expanded to wider fields provided that strong magnetic field can be utilized for enhancing the functions of plasma. Experimental studies of functional enhancement of the plasma jet in the magnetic field have previously been made to examine the effects of magnetic field on the flow(3)–(5). However, sufficient data on the flow characteristics have not been obtained under the strong magnetic field induced by a superconducting magnet. To realize the progress of plasma technology, it is necessary to understand the flow characteristics of plasma under various conditions.

It is well known that the effect of strong magnetic field on the conducting flow can be explained mainly as \( j \times B \) force(6). Nevertheless, the influences of this electromagnetic force on the flow behavior are considerably complicated; for example, the force significantly depends on the plasma properties such as Hall effect. Therefore, it is crucial to clarify the flow characteristics under the strong field by using the experimental approach.

From these points of view, emission measurement on plasma jet was previously conducted in the strong magnetic field(7)–(9). The excitation temperature was also obtained on the basis of the relative line intensity. The behavior of argon plasma jet in a vacuum chamber was observed through the window in the present paper. The images of the jet were taken by a digital camera when strong magnetic field was applied to the jet by means of superconducting coils. The effect of strong magnetic field on the jet was evaluated quantitatively from the image analysis. Measurement on emission from the plasma jet under the strong magnetic field was also carried out to compare the image analysis. Moreover, excitation temperature was determined from the measurement results.

Nomenclature

\( A_{bina} \) : area of brightness region determined from binarized image

\( B_c \) : magnetic flux density at midpoint between coils in the case of coils A and B

\( B_{max} \) : maximum magnetic flux density in the case of only coil A

\( I_p \) : emission intensity from plasma

\( i_c \) : persistent current

\( i_s \) : supplied current to plasma torch

\( L \) : distance from the torch exit plane to the central axis of optical probe
mass flow rate
background pressure
excitation temperature
threshold value for binarization
width of brightness region determined from binarized image
axial coordinate
vertical coordinate

2. Experimental Setup and Procedures

Plasma jet was generated by a plasma torch in a chamber with a vacuum pump system in the present experiment. Argon was employed as working gas. Figure 1 represents the vacuum chamber in plan view. It also shows schematic view of the arrangement of apparatus in the chamber. The background chamber pressure \(p_b\) was maintained at \(393 \pm 14\) Pa when the plasma jet was operating at mass flow rate of \(\dot{m} = 1.23 \pm 0.01\) g/s. The jet from the torch went through the magnet bore. The magnet consists of a pair of superconducting coils. Each coil has the same specification and can produce a field in excess of 3 T. The present experiment was done in the cases that both coils, coils A and B, operate and that only coil A operates. Figure 2 illustrates magnetic field distribution along the centerline of the magnet bore in the case of coil current \(i_c = 35.72\) A. In the case of coils A and B, the magnetic flux density at midpoint between coils, indicated by \(x = 0\) mm in this figure, is referred to as \(B_c\). \(B_c\) is 0.5 T for \(i_c = 35.72\) A. Since maximum magnetic flux density is more than 1 T, such a strong field is not easily attainable with the ordinary solenoid. \(B_c\) reaches 1.5 T in the case of the maximum specified current \(i_c = 1071.16\) A. Similarly, when only coil A operates, the maximum magnetic flux density is referred to as \(B_{max}\). \(B_{max}\) is 1.0 T for \(i_c = 35.72\) A. It achieves 3.0 T for \(i_c = 1071.16\) A. The behavior of the jet between two coils was taken by a digital camera through the window for observation. The emission measurement on the plasma jet was also conducted by using an optical probe at the opposite side of the window. The emission at lateral positions from the center to the outer edge of the jet in 1 mm intervals was collected by a lens system at the head of the optical probe. The arrangement of optical probe and traverse assembly is schematically illustrated in Fig. 3. The distance along the centerline between the torch exit plane and the focused point of optical probe, \(L\), was set to be 400 mm before measurement.

3. Results and Discussion

3.1 Image analysis

Image analysis was carried out by using binarization. The color lighter than the threshold value, \(V_{bin}\), is converted to white and any color darker than the value to black in the binarization. In this study, Adobe Photoshop was employed for the analysis. Figure 4 illustrates examples of raw images and images after binarization for \(B_c = 1.5\) T. The original images are taken in the cases of the supplied current to plasma torch \(i_c = 175\) A (the left image) and \(i_c = 200\) A (the right). Examples of binarized images in the case of threshold value \(V_{bin} = 180\) are shown in Fig. 4 (b). The maximum value of \(V_{bin}\) is 255 since the resolution of color is 8 bit, or 256. The width of white area, \(W_{bin}\), was measured.

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**Fig. 1** Arrangement of apparatus in vacuum chamber


**Fig. 2** An example of magnetic field distribution

**Fig. 3** Optical probe and traverse assembly


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JSME International Journal
measured in the center of the observed image. The area of white, $A_{bin}$, was determined from total number of white pixels and the spatial resolution of image.

Figure 5 represents examples of the binarized images under the condition of $i_s = 200\ A$ for coils A and B. Naturally, the white area decreases with increases in the threshold value $V_{bin}$. In the case of $V_{bin} < 180$, the white area obviously decreases with increases in the magnetic flux density. On the other hand, the white area in the case of $V_{bin} > 220$ increases with increases in $B_c$. Figure 6 indicates the results of the width $W_{bin}$. The width $W_{bin}$ decreases with increases in magnetic flux density in the case of $V_{bin} < 210$. On the contrary, the width $W_{bin}$ increases with the field intensity in the case of $V_{bin} > 230$.

Figure 7 illustrates the effects of the magnetic flux density on the brightness area. The high brightness region in the case of $V_{bin} = 240$ increases with the magnetic flux density $B_c$. However, the low brightness region in the case of $V_{bin} = 140$ decreases with increases in $B_c$. From these results, it is considered that the jet spreads out in the chamber under the condition of no magnetic field and that it is constricted with the application of magnetic field. Figure 8 shows the width $W_{bin}$ for $i_s = 175\ A$. It shows the same tendency as Fig. 6. Since the input power into the jet is low in comparison with that for $i_s = 200\ A$, the low brightness region ($V_{bin} < 200$) becomes slightly large. These results indicate evidently that the plasma jet is constricted with strong magnetic field and that high bright-
ness region around the center of the jet increases with the strong magnetic field. It has been inferred from the previous studies\cite{7,8} that the excitation temperature is higher in the high brightness region. It is considered that the width of high temperature region increases because the high temperature portion is pushed out downstream due to the compression of the jet.

The plasma jet is very slightly influenced by the field in the case of $B_c = 0.25\ T$ as shown in Fig. 7. However, it is indicated that it is necessary to apply the field of $B_c \geq 0.5\ T$ for both coils to compress the jet clearly. It is considered that the strong field of $B_c \geq 1.0\ T$ is needed to change the energy density distribution in aspect of the plasma control by using the strong magnetic field.

Figure 9 shows the results of the width $W_{bin}$ in the cases of coil A and $i_s = 200\ A$. It indicates the same trend as Fig. 6. However, the width $W_{bin}$ is wider than that for coils A and B under the condition of applied magnetic field. It is confirmed from the image analysis results that the plasma jet is compressed radially by the strong magnetic field.

### 3.2 Emission intensity and excitation temperature

Figure 10 shows the evolution of the typical spectral intensity with lateral distance from the center of the coil bore in the case of coils A and B. $I_{P_{\text{max}}}$ represents maximum value of emission intensity $I_p$ at $B_c = 1.5\ T$. The data described here were obtained for $i_s = 200\ A$ by scanning the monochromator from 564 – 623 nm in wavelength. The spectral intensity without magnetic field declines gently to the outer edge of the jet. The intensity for $B_c = 1.5\ T$ rises around the center of the jet and drops considerably toward the outer edge. $I_p/I_{P_{\text{max}}}$ shows similar trend among independent wavelengths. By the way, emission intensity is defined as Eq. (1).

$$I_p = \frac{hc}{\lambda \beta} A_{ji} n_j$$

where $h$ is Plank’s constant, $c$ is velocity of light in a vacuum, $A_{ji}$ is Einstein coefficient for spontaneous emission.
and $n_j$ is the number density of the upper excited level. Subscripts $j$ and $j'$ are the lower and the upper energy level, respectively. Subscript $ji$ means the transition from $j$ to $i$. The relation between typical spectral intensity $I_p$ and the number density $n_p$, is presented in Eq. (2).

$$\frac{I_p}{I_{p\text{ max}}} = \frac{I_{pji}}{I_{ji\text{ max}}} = \frac{n_j}{n_{ji\text{ max}}}$$

Since $I_p/I_{p\text{ max}}$ corresponds to $n_j/n_{ji\text{ max}}$, it was concluded that the number density at the center portion of the jet becomes high with the application of the field. Therefore, it is confirmed from the results of emission measurement that the plasma jet is compressed with strong magnetic field and that the constriction becomes strong as the field strength increases.

Figure 11 also shows the typical spectral intensity in the case of coil A. $I_{p\text{ max}}$ defines as maximum of $I_p$ at $B_{\text{max}} = 3.0\, \text{T}$. It shows the same tendency as Fig. 10. The intensity drops moderately toward the outer edge since magnetic field strength is weaker than that for coils A and B.

Figure 12 indicates the variation of the excitation temperature with the lateral distance from the center of bore for $i_s = 200\, \text{A}$. The results of the excitation temperature show the same trend as the spectral intensity. It is also confirmed from the present experimental results that the plasma jet is constricted with the magnetic field. Thus, it is found that it is possible to control significantly the flow behavior of plasma jet by using the strong field.

4. Conclusion

Fundamental studies were carried out to control the flow characteristics of plasma jet by using the strong magnetic field applied by the superconducting magnet. In the present paper, the effect of the field on the jet was evaluated quantitatively from the image analysis. The results obtained here are summarized as follows.

(1) It was indicated that the plasma jet is constricted radially by the strong magnetic field and that the constriction becomes strong as the field strength increases.

(2) It was shown that high brightness region around the center of the jet increase with the field strength due to the influence of the constriction of the jet.

(3) From the results of emission measurement, it was considered that the number density of the upper excited level at the central region of the jet becomes high with the application of strong magnetic field.

(4) It is confirmed that the strong magnetic field induced by the superconducting magnet is needed to change the energy density distribution of the plasma jet in aspect of the plasma control.

References


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