International Research Journal of Applied and Basic Sciences
© 2014 Available online at www.irjabs.com
ISSN 2251-838X / Vol, 8 (7): 944-950
Science Explorer Publications

External Transverse Direct Current Magnetic Field Effect On Optical Emission Of a Non-Thermal Atmospheric Pressure Argon Plasma Jet

Reza Safari[1]

1. Department of Atomic and Molecular Physics, Faculty of Basic Sciences, University of Mazandaran, Babolsar, Iran

Corresponding Author email: reza8_safari@yahoo.com

ABSTRACT: An experimental study of plasma jet at atmospheric pressure was carried out to examine the influence of external transverse magnetic field on it. A magnetic field was applied to the jet in atmospheric pressure by means of a pair of coils, same Helmholtz coil configuration. It was applied transverse to the jet flow. The strength of the direct current magnetic field was 0- 0.057 Tesla between the two coils in parallel application. It was shown that the plasma gas flow plays the main role in magneto-active collision-dominated plasma. The effect of plasma fluid velocity on the jet emission was discussed, qualitatively. The measurements revealed that the plasma jet irradiance decreases in parallel field. The former was attributed loss of plasma species that reduces the magneto-plasma jet irradiance and in turn shrinks plasma jet number density. As a result, it was concluded that the plasma fluid velocity lead to decrease optical radiation intensity.

Key words: Non-thermal atmospheric pressure plasma jet, Direct current external magnetic field, Magneto-active collision-dominated plasma

INTRODUCTION

Plasma is a gas with enough energy to ionize a significant fraction of its atoms or molecules, forming equal numbers of positive ions and electrons. There are free charges and ambipolar pairs in plasmas; overall the negative and positive charges compensate each other. Therefore, plasmas are electrically neutral, a property known as quasi-neutrality. Plasmas cover a wide range of pressures, temperatures, and electron densities. There are two main types of plasmas, atmospheric pressure and low pressure. For atmospheric pressure plasmas, the mean free paths between electrons and heavy particles are extremely short and, therefore, the plasma is collision dominated. About atmospheric-pressure plasmas, there are two distinct categories, thermal and non-thermal plasma. Much interest has been focused on industrial applications of cold plasmas such as materials processing and the development of new materials. In these applications, it is important to identify and study the plasma jet characteristics under various conditions. From this point of view, much experimental and numerical investigation has been carried out to identify plasma jet characteristics (Schutze et al., 1998; Bogaerts et al., 2002; Kogelschatz, 2004).

Atmospheric pressure plasma jet (APPJ) is one of the various types of plasma sources, with different configurations, where most of the jets are working with noble gas mixed with a small percentage of reactive gases, such as O_2 (Lu et al., 2005). Dielectric barrier discharge (DBD) plasma jet is one of different configurations that operate with noble gases. Plasma generated in this configuration, is a cold plasma. The DBD jet devices can be operated either by kHz ac power or by pulsed dc power. In this work, DBD configuration and pure argon are used and the APPJ was driven by a sinusoidal alternating high voltage power supply 15 kV with frequency, 10 kHz.

In order to study of plasma characteristics, behavior of thermal argon plasma jet in vacuum chamber was observed when the strong magnetic field was applied to the jet. It was indicated from the observation that the jet radially compresses with the application of the strong magnetic field and that the high temperature region in the middle of the jet becomes much brighter with the strong magnetic field than without magnetic field(Koike et al., 2004; Koike and Ono, 2008; Ono et al., 2006; Ono et al., 2007).

The issue of external parallel magnetic field effect, on non-thermal atmospheric pressure plasma jet has not been studied, yet. In this research, an experimental study was carried out to examine the external parallel direct current (DC) magnetic field effects on non-thermal atmospheric pressure plasma jet. Here after, plasma jet in external magnetic field is named magneto-active atmospheric pressure plasma jet (M-APPJ). We utilized optical emission spectroscopy (OES) apparatus and imaging technique to quantify the plasma jet behavior under different conditions. In this research, a collisional magneto-active atmospheric pressure plasma is studied, therefore, the transport phenomena behavior seems not to be the same as a typical low pressure magneto-active gas discharge, although the strength of the DC magnetic field is moderately high. Look at mobility, conductivity and diffusion tensors elements in the presence of external magnetic field (Krall and Trivelpiece, 1973)

$$\mu_{\perp}=\frac{q\nu_m}{m\left(\nu_m^2+\omega_c^2\right)} \qquad \mu_T=\frac{q\omega_c}{m\left(\nu_m^2+\omega_c^2\right)} \qquad \mu_{\parallel}=\frac{q}{m\nu_m} \qquad (1)$$

$$\sigma_{\perp}=\frac{nq^2}{m\left(\nu_m^2+\omega_c^2\right)} \qquad \sigma_T=\frac{nq^2\omega_c}{m\left(\nu_m^2+\omega_c^2\right)} \qquad \sigma_{\parallel}=\frac{nq^2}{m\nu_m} \qquad (2)$$

Where q is the electron charge, ν_m and ω_c are electron collision frequency for momentum transfer and electron cyclotron angular frequency, respectively. n and m are the electron number density and mass, respectively.

Regarding to reference (Raizer, 1997), one can find that for an atmospheric pressure plasma jet in T_e=1ev, $\nu_m=4.028\times10^{12}s^{-1}$ and $\omega_c=7\times10^{10}rad.s^{-1}$ with external direct current magnetic field of B=4000 G. While for a typical low pressure plasma at p=1mTorr, $\nu_m=5.3\times10^{6}s^{-1}$ and $\omega_c=7\times10^{10}rad.s^{-1}$ with the same magnetic field strength as before. It is seen that in our case $\left(\omega_c/\nu_m\right)^2 \ll 1$, while in low pressure case, $\left(\omega_c/\nu_m\right)^2 \gg 1$.

This means at atmospheric pressure, when $\left(\omega_c/\nu_m\right)^2 \ll 1$, collisions make the magneto-active collisional plasmas to be isotropic for transport phenomena in which mobility, conductivity and diffusion play roles. Although the applied magnetic field is moderately high, but $\mu_{\perp}=\mu_{\parallel}$, $\mu_T\cong0$. This also holds for conductivity. As a result, the aforementioned tensors lead to be a scalar coefficient for magneto-active atmospheric pressure plasma jet in the presence of external magnetic field. The question still remains, how the external magnetic field influences the collision-dominated plasma jet? One can address the interaction between the plasma fluid velocity $\vec{V}$ and the DC external magnetic field irrespective of collision frequency (pressure) as the answer to this question. Charged particles moving with the gas will experience an induced electric field proportional to $\vec{V}\times\vec{B}$ which will tend to drive an electric current in the direction perpendicular to both $\vec{V}$ and $\vec{B}$. In this work we neglect the Hall effect and estimate the magnitude of the current density for the weakly ionized collision-dominated plasma jet by the generalized Ohm's law. Therefore, the plasma fluid velocity direction plays the main role in magneto-active plasma jet behavior.

To explain this problem, analytical models for magneto-active atmospheric pressure plasma jet behavior, MHD fluid equation is presented.

In this research, we studied the effects of external parallel magnetic field on cold atmospheric pressure argon plasma jet that in section 2, we present the experimental setup and methods are presented, in section 3, we discuss about the experimental results. Discussions and analytical models will be given in section 4. Finally, conclusions will be given in section 5.

Experimental setup and models

Figure 1 shows the experimental setup and method in this study. The APPJ consists of a tube of Pyrex glass with a length of 35 mm. Powered electrode was set inside the Pyrex tube and grounded ring electrode was attached to the surface of the Pyrex nozzle. The APPJ was generated at the gas gap between two copper electrodes and exited into the surrounding air outside the nozzle (Fig. 1a). The flow rate of working gas, argon, was 5 lit/min that controlled with a mass flow controller. In addition, the jet length was about 20 mm which measured from the nozzle orifice. The maximum width of the jet was 3 mm. The strength and configuration of the external magnetic field in transverse state were shown in figure 1b and figure 1c, respectively.

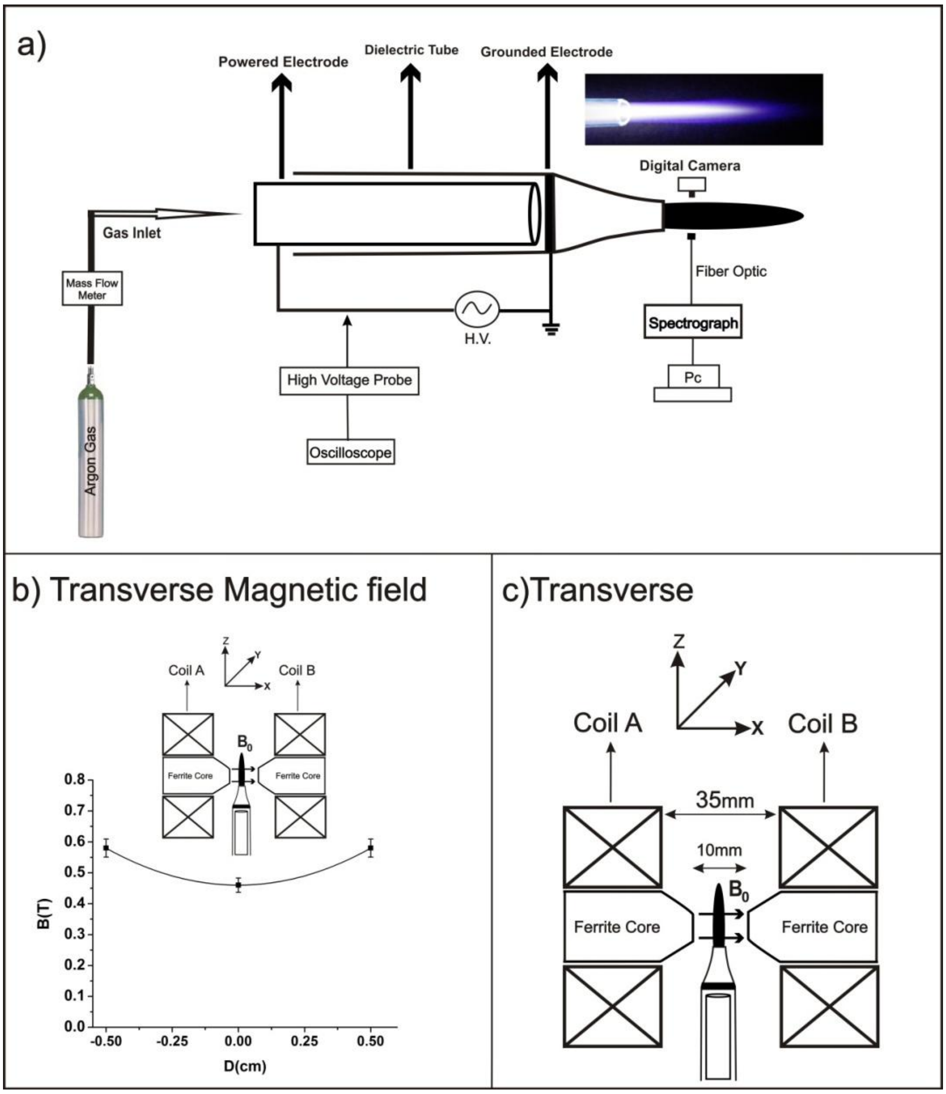

Figure1. (a) Schematic picture of the APPJ set up (b) magnetic field strength in transverse state (c) transverse application of the direct current external magnetic field on the APPJ.

The APPJ was driven by a sinusoidal alternating high voltage power supply 15 kV with frequency of 10 kHz. Electronic Block diagram of power supply that had been used to apply high voltage is shown in figure 2.

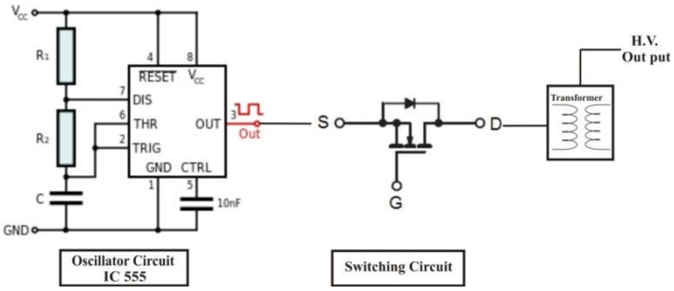

Figure2. Electronic Block diagram of power supply

Separation between the two coils in transverse states was 3.5 cm. To measure the magnetic field, a Tesla-meter (Leybold-Heraeus530) was used. The measurements showed that there is good agreement between computational and measured magnetic field strength. In order to increase magnetic field strength, we inserted ferrite cores into the coils. The dimension of the ferrite core was $26\times26\times80m^3$. In the transverse case, ferrites were sharpened at one end leading to minimum magnetic field strength of 0.46 Tesla with 10 mm separation between two sharped ends. The magnetic field evolution for transverse application is depicted in figure 1b.

Finally, the magnetic field strength applied to plasma jet, was at focused point for optical intensity measurement, about 0.46 Tesla in transverse form in the case of the maximum specified current of power supply, I=18 A.

To record the emission of the jet, we employed UV-IR compact wide range 190-1100 nm spectrometer (S-100, Solar-Laser system). To capture the photograph of the jet and process the intensity profile, a digital camera (SONY PSC-HX-20 18.1 Megapixel) was used. The focused point for intensity measurement by spectroscopy and photography methods was shown in figure1a. In this point, the width of jet is about 3mm. During OES, argon emission spectra was measured at vertical position to the jet direction and to the magnetic field direction. The relationship between the emission intensity I_p and the optical radiation intensity I is estimated by the following expression

$$I \propto \int I_P d\lambda \;, \qquad (3)$$

where, λ is the wavelength.

After running the jet, the temperature of plasma jet increases gradually. For example: it raises from room temperature to 50 °C in 20 minutes. it leads to the plasma number density increase. The APPJ irradiance increases gradually due to gas temperature increase. Temperature increment takes place both with and without magnetic field. To decompose gradually increment of temperature effect from that of the magnetic field, OES was taken in discrete and continuous forms. In discrete form, by spectroscopy, argon spectra emission was collected with optical probe, 60 seconds after ignition. Then the jet was turned off for several minutes for cooling. Then it was generated again and its emission was recorded in the presence of the magnetic field. This method guarantied the same temperature for plasma measurements.

In the continuous form, the plasma jet wasn’t turned off during the measurements; instead, the external magnetic field was switched off in time intervals. Plasma jet was generated and after 10 seconds, by spectroscopy, the jet emission was collected, then after 60 seconds, its emission was recorded again. In the next process, magnetic field was applied and after 60 seconds, the jet emission spectra was recorded. Then its emission was collected after 60 seconds in magnetic field-free and in final process, magnetic field was applied again and plasma jet emission was recorded. Both continuous and discrete forms were carried out by photography in conjunction with OES.

EXPERIMENTAL RESULTS

In this section, the effect of transverse magnetic field on plasma jet is investigated. In the discrete case, figure 3 shows comparison between argon emission spectra in the presence and absence of the external magnetic field in the transverse state. As shown in figure 3, the emission intensity decreased at all wavelengths.

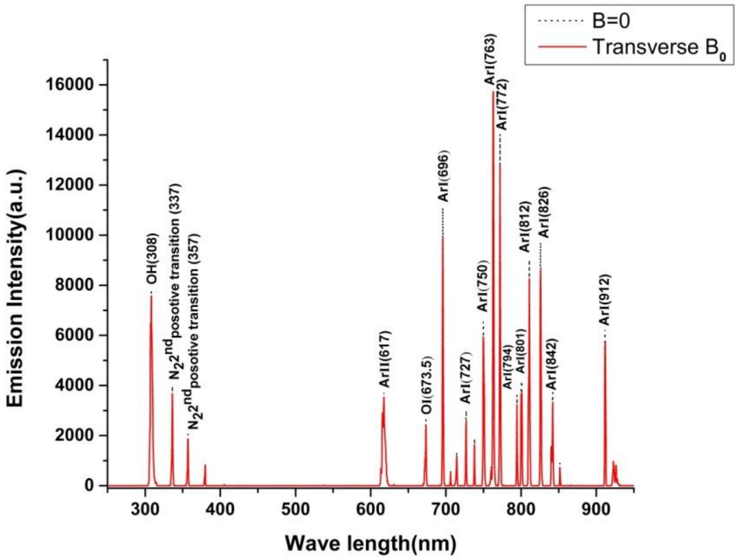

Figure3. Comparison between argon emission spectra in the presence and absence of the transverse external magnetic field

The variation of the optical radiation intensity obtained from imaging technique and spectroscopy method, in the discrete form, was shown in figure 4. In the presences of the external transverse magnetic field, the optical radiation intensity of the jet decreased.

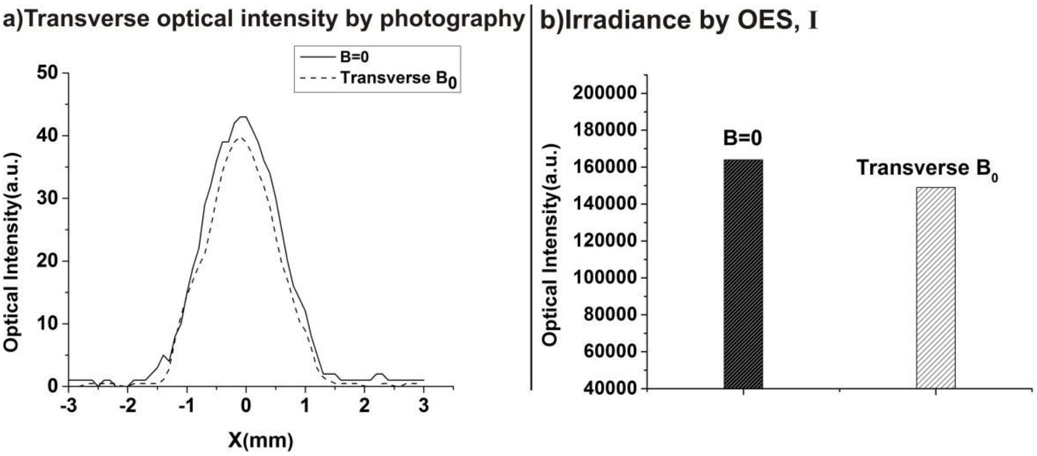

Figure4. The variation of the optical radiation intensity in the presence of the transverse magnetic fields, by (a) imaging technique and (b) Spectroscopy method

As mentioned, image analysis software was utilized to obtain the optical radiation in transverse and axial directions with respect to the flow velocity. Figure 5 shows transverse magnetic field effect on the optical radiation intensity distribution along with the jet flow in the discrete form.

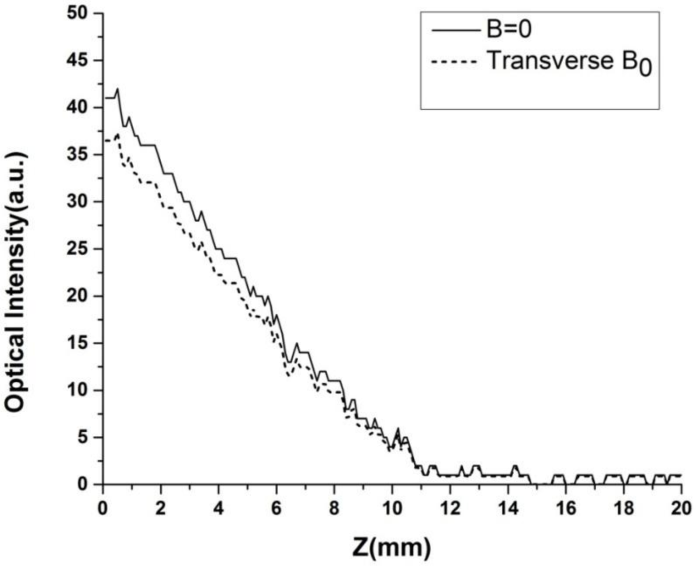

Figure5. The variation of the optical radiation intensity in the presence of the transverse magnetic field, along the jet flow direction, captured by the camera

In presence of transverse magnetic field, optical intensity in direction of the centerline axis, decreased. These results indicate that the distribution of optical radiation intensity in this direction is in good agreement with vertical direction. Figure 6 shows the relationship between optical radiation intensity that was recorded by the spectroscopy and the photography methods in the case of the transverse magnetic field in continuous form.

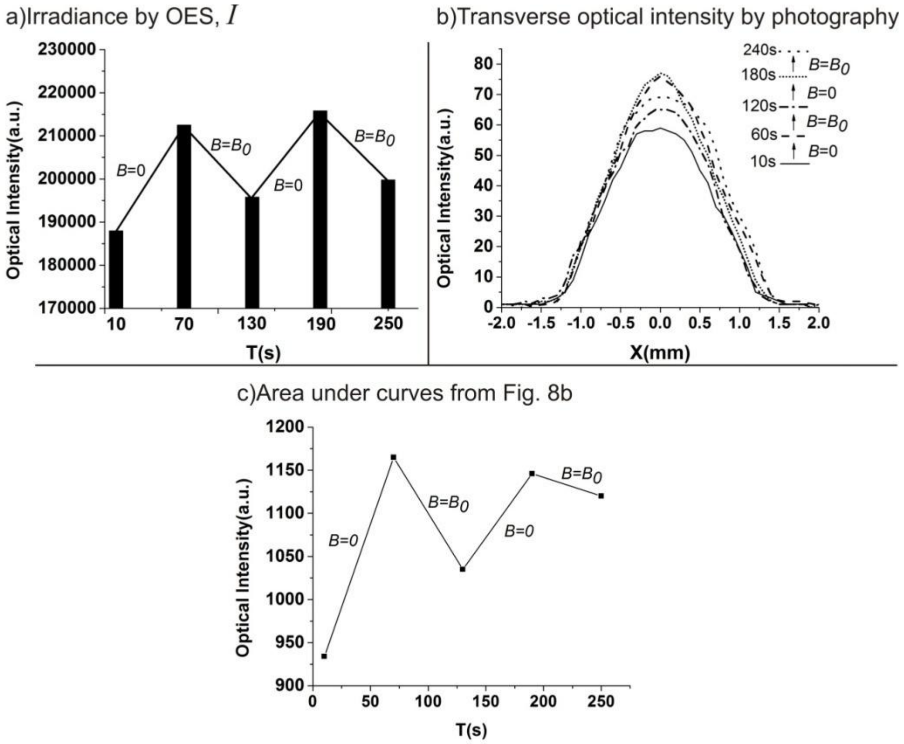

Figure6. The variation of the optical radiation intensity in the presence of the transverse magnetic field, in the continuous form by (a) Spectroscopy method and (b) Imaging technique

As can be observed, by applying the external magnetic field transversely, the optical radiation intensity decreased while in field-free case, it was increased due to gradually increment of the plasma jet temperature.

DISSCUSSION AND ANALYTICAL MODELS

In this paper, the OES and the imaging technique were utilized to quantify the plasma jet behavior under the external transvesre magnetic field. The distribution of the optical radiation intensity obtained from raw image files, agree well with that of the spectral intensity in discrete situation. Application of the external magnetic field, transverse to the plasma jet flow leads to drift motion of ions and electrons in opposite direction and finally generate a current density, perpendicular to the magnetic field and to the jet flow. In this zone, there is not a considerable applied electric filed but there can be an induced electric field based on $\vec{V} \times \vec{B}$ term , where $\vec{V}$ is the flow velocity vector. The magnetic field density flux in spectroscopic zone was about 0.46 Tesla. As shown in Fig. 1c, magnetic field is in X-direction and plasma jet flow is in Z-direction and is perpendicular to $\vec{B}$. The problem of the plasma jet flow perpendicular to the magnetic field is well known and the induced current density due to magnetic force can be deduced from MHD Ohm's law

$$J_y = \sigma\left(V_Z B_x + E_y\right) \qquad (4)$$

Where, E_y is the induced electrostatic electrical field. This process led to transportation of charged particles from the plasma jet zone and in turn shrinks the plasma number density. In this case, the circuit is open, then the current density along with Y-direction is zero. For the characteristic conditions $V \sim 30m/s$, and B=0.48T, the open circuit electric field is $VB \sim 15V/S$. For the case we studied, the diameter of the jet was about 3 mm. Then the induced potential difference is estimated to be 45 mV. This led to plasma loss and reduced the plasma irradiance.

CONCLUSION

An experimental study was carried out to clarify non-thermal atmospheric pressure plasma jet behavior under the application of the external magnetic field, in the transverse form. Although the applied magnetic field was moderately high, but the non-zero transport tensor elements are the same and make M-APPJ to be isotropic. This indicates that the plasma description is not the same as low pressure magneto-active plasmas. As we treated the APPJ under external magnetic field, analytical models for M-APPJ behavior using MHD fluid was presented. The optical radiation intensity that was recorded by camera and OES methods was analyzed to observe the magnetic field effects on the jet. The external magnetic field was generated by Helmholtz coil configuration. The strength of the DC filed was about 0.46 Tesla between two coils in transverse configuration. As a result, the related mobility and conductivity tensors are to be scalar coefficients for M-APPJ in the presence of external magnetic field. This investigation confirmed that the magneto-active atmospheric pressure plasma description is not the same as that of low pressure. When the magnetic field is applied transverse to the jet flow, OES and imaging technique revealed reduction in the jet irradiance and it was described by MHD Ohm's law equation. It was concluded that the plasma fluid velocity is responsible for changes in magneto-active plasma jet irradiance via magnetic force $\vec{V} \times \vec{B}$, where V is the flow velocity vector. The results of this work can be used to control the plasma jet number density.

REFERENCES

Bogaerts A, Neyts E, Gijbels R, Van der Mullen J. 2002. Gas discharge plasmas and their applications. Spectrochimica Acta Part B: Atomic Spectroscopy. 57:609-658.

Kogelschatz U. 2004. Atmospheric-pressure plasma technology, Plasma Physics and Controlled Fusion. Vol. 46.

Koike K, Ono N, Watanable Y, Musha K. 2004. Measurement on the excitation temperature of argon plasma jet under strong magnetic field. Vacuum. 73: 353-358.

Koike K, Ono N. 2008. Light intensity analysis of plasma jet constriction with applied magnetic field. Vacuum. 83: 25–28.

Krall NA, Trivelpiece AW. 1973. Principles of Plasma Physics. McGraw-Hill, New York.

Lu X, Laroussi M, Puech V. 2005. On atmospheric-pressure non-equilibrium plasma jets and plasma bullets. Plasma Sources Sci. Technol. Vol. 21.

Ono N, Musha K, Koike K. 2006. A simple diagnostic method for plasma jet in strong magnetic field. Vacuum. 80: 1179-1184.

Ono N, Otomo Y, Koike K. 2007. Behavior of Underexpanded Plasma Jet in Strong Magnetic Field. J. Visualization. 10: 237-244.

Raizer Yu P. 1997. Gas Discharge Physics. Springer, Verlag Berlin Heidelberg.

Schutze A, Jeong JY, Babayan SE, Park J, Selwyn GS, Hicks RF. 1998. The atmospheric-pressure plasma jet: a review and comparison to other plasma sources. Plasma Science, IEEE Transactions on. 26: 1685-1694.