Comparative Study of Optical Emission Spectroscopy and Electric Probe Measurements for Visible Light Tomography in Low Pressure Microwave Plasma

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Microwave induced Argon and Hydrogen plasma confined in a multicusp is studied in the pressure range of 0.2 to 0.8 mTorr and microwave powers of 216 to 324 W. The plasma parameters such as electron temperature (T_e) and density (N_e) are evaluated using optical emission spectroscopy (OES) and Langmuir probe measurements. The estimated electron temperature (T_e) and density (N_e) from OES measurements lie in the range 5 – 11 eV and 1.5×10^{10} cm^{-3} to 4.0×10^{10} cm^{-3} respectively for the Ar plasma, while corresponding values for hydrogen plasma are 6 – 13 eV and 0.6×10^{10} to 3.5×10^{10} cm^{-3}. The plasma parameters estimated from OES are compared with the values estimated from the Langmuir probe measurements. The objective of the present work is to develop a visible light tomographic measurement system for plasma confined in a compact multicusp. In general, optical emission spectroscopy is carried out to know the wavelengths of most intense emitted light from the plasma.

1. Introduction

Microwave induced plasmas (MIP) have been widely applied for ion beam sources [1] , thin film deposition [2], etching process [3] and for various other industrial purposes. Several basic plasma physics studies, such as diffusion of plasma particles, interaction of plasma particles with electromagnetic waves in bounded plasma column [4] have been carried out in MIP. In order to consider applications of MIP in industry and future research, development of plasma diagnostics is required. Plasma diagnostics provide both basic understanding of plasmas and are also useful indictors for monitoring plasma processes. It is desirable to know important parameters, such as electron temperature and density over the entire spatial extent of the compact plasma system. For this optical tomography can provide a solution, because it provides a way to measure optical emission from the entire plasma and by tomographic reconstruction [5] a complete image of the plasma can be understood in terms of density, temperature and emission profiles. This can shed valuable light on important processes going on inside the plasma such as wave absorption and reflection, including instabilities and other non-linear phenomena [6].

In the present work, we have identified experimentally the principal wavelengths emitted from the microwave induced plasma and have utilized this information to determine the plasma parameters such as electron temperature and density under different discharge conditions. We have also verified the obtained results from OES method using electrostatic Langmuir probe to see how well they agree. The information of the most intense wavelengths is used to design optical filters for the tomographic system.

2. Experimental

A schematic diagram of the experimental setup with Langmuir probe (LP) and optical emission spectroscopy system is presented in Fig 1(a). Microwave of 2.45 GHz generated from a microwave generator is passed through standard rectangular waveguides and through a quartz window into a multicusp (MC), kept inside a vacuum chamber (VC). The operating gas pressure is varied in the range of 0.2 – 0.8 mTorr for both working gases (Ar and H_2). The pressure inside VC is controlled by using a mass flow controller (Model No. 246C, MKS). The plasma is confined using an octupole MC [7] as shown in Fig 1(b). The OES set up is attached to one diagnostics port which provides a line of sight through the plasma. The basic detection system consists of an optical fiber and a spectrometer. The optical fiber is fixed in the gap between two magnets of MC, as shown in Fig 1(b).

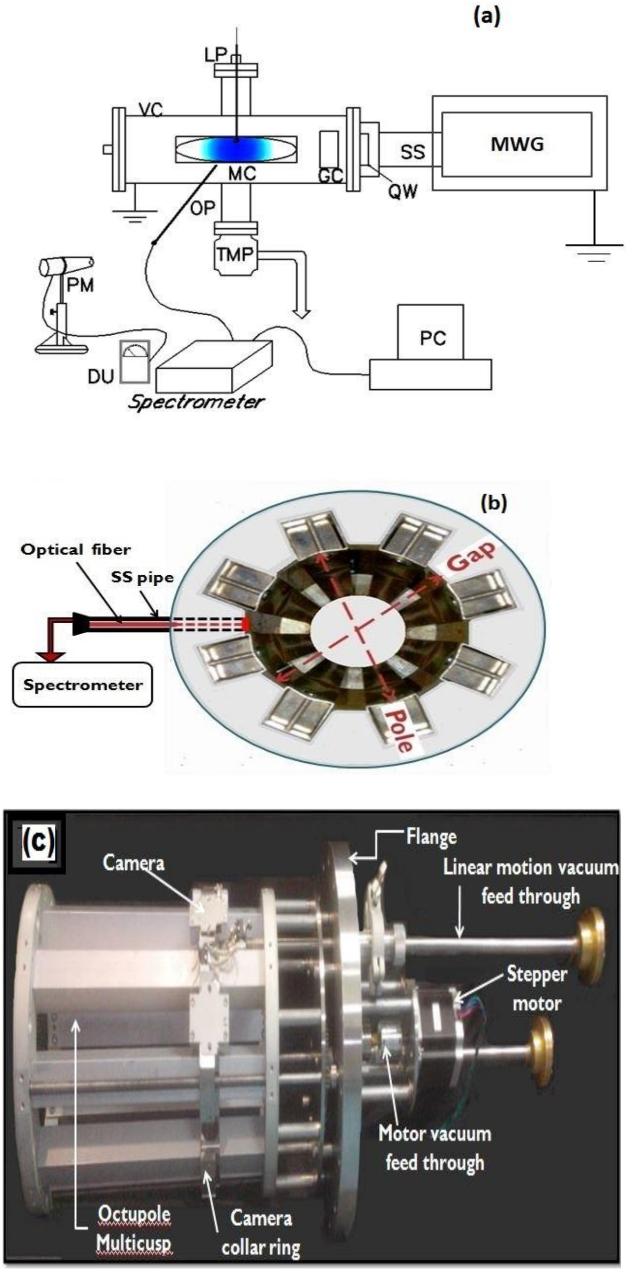

Fig 1(a) Schematic of the experimental set up. VC: vacuum chamber, MC: multicusp, GC: guiding cylinder, TMP: turbo molecular pump, QW: quartz window, SS: straight waveguide section, MWG: microwave generator, LP: Langmuir probe, PC: personal computer, OP: optical probe, PM: power meter, DU: display unit for power in W for specific wavelengths. (b) Cross sectional view of MC (c) experimental set up for optical tomographic measurement system for multicusp plasma

On the basis of spectroscopic measurement results, we have developed the optical tomographic set up for the MIP. The tomographic set-up consist of several pin hole cameras (eight in numbers) at 45 degree view angle. The camera collar ring can move linearly on the length of the multicusp with step of 1 mm using a stepper motor as shown in Fig 1(c). A single pin hole camera consists of a 150 micron slit, aspheric lens and an optical filter which can be changed (e.g. 750 nm, 772 nm, 811 nm, 486 nm and 656 nm). There is a linear array of photodiodes sensitive in the wavelength range of 400 nm – 1000 nm. Visible light from the plasma is collected in the form of line integral for peak wavelength of Ar and H_2 plasma. Tomographic reconstruction techniques can be used for reconstructing images of spatially resolved emissivity profile of multicusp plasma using line integral measurements, which will be reported in the future.

3. Results and Discussion

The OES measurements have been performed to get insight of line intensity of argon and hydrogen plasma, for developing the tomographic system. Fig. 2(a) presents optical spectrum of Ar plasma at 0.6 mTorr pressure and 324 W microwave power. Ar spectra show some intense atomic lines in the red to near–infrared region that are 696.54 nm, 750.39 nm, 751.47 nm, 763.51 nm, 772.38 and 811.53 nm (Transitions 2p → 1s) as well as ionic lines 419.8 nm, 420.1 nm, 425.9 nm and 430 nm (Transitions 3p → 1s). Relative intensities of the ionic lines are much lower compared to the atomic lines and they may be neglected since their contribution to the total emitted power is very low. Figure 2(b) shows optical spectrum of molecular hydrogen plasma at the same power and pressure as in Ar plasma (Fig. 2(a)). The three strong Balmer atomic emission lines $H_\alpha (n=3 \rightarrow n=2)$ at 656.25nm, $H_\beta (n=4 \rightarrow n=2)$ at 486.13 nm and $H_\gamma (n=5 \rightarrow n=2)$ at 434.06 nm are clearly observed. The Fulcher α $(d\,^3\prod_u - X\,^3\sum_g)$ molecular hydrogen band is observed in the wavelength range of 590 nm – 640 nm. It is clearly visible that atomic H_α, H_β and H_γ lines are more prominent in relative intensity as compared to molecular energy band wavelength region.

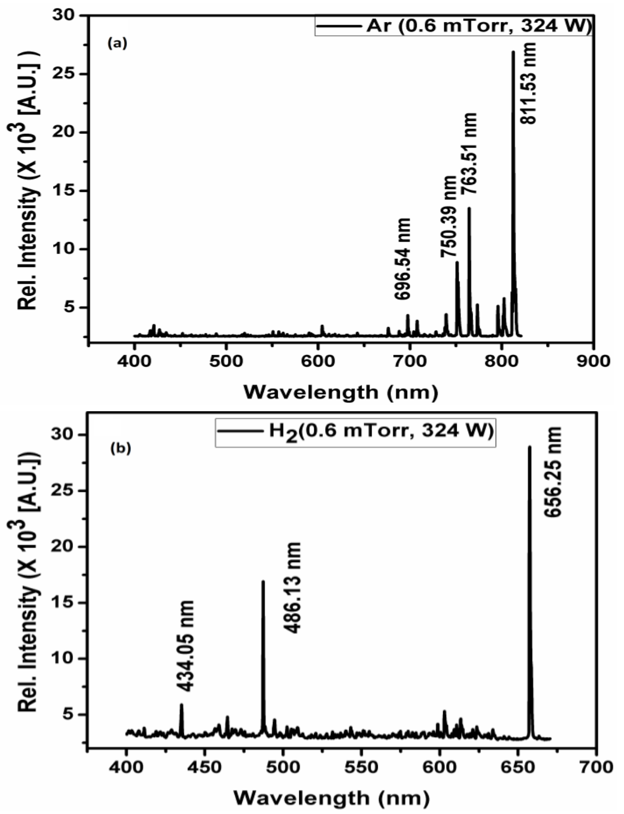

Fig 2. Optical emission spectrum of, (a) Ar plasma and (b) H_2 plasma at gas pressure of 0.6 mTorr and 324 W of microwave power.

Optical diagnostics of plasma require models on the basis of population density in excited states for their description as belonging to non-Local thermodynamic equilibrium (LTE). Non-LTE plasma as function of pressure and power satisfies corona equilibrium (CE) model and the criteria is given by Fujimoto [8] for hydrogen and other rare gas plasmas. CE model assumes that the ionizing plasma consists of direct excitation from ground state by electron-impact collisions and is depopulated by radiative decay. Corona balance equation [9 -10] can be written as,

$$N_e N_1 k_{1i} = N_i \sum_{i>j} A_{ij} \quad , \qquad (1)$$

where N_e, N_1 and N_i are respectively the electron, ground level and excited state population densities, k_{1i} is the electron impact excitation rate coefficient from ground state 1 to level i and $\sum_{i>j} A_{ij}$ is the sum of all possible spontaneous radiative transition from upper energy level j to level i. In order to calculate the electron temperature, we have used the modified Boltzmann formula [9]

$$\ln\left(\frac{I_{ij}\lambda_{ij}\sum_{i>j} A_{ij}}{A_{ij}a_{1i}}\right) = -\frac{E_{1i}}{kT_e} + Const \quad , \qquad (2)$$

where I_{ij}, λ_{ij} and A_{ij} are respectively the intensity, wavelength and Einstein coefficient of spectral lines, T_e is electron temperature, a_{1i} is the coefficient in an exponential approximation of electron impact excitation rate coefficient from ground state 1 to level i and E_{1i} is the excitation energy from ground state 1 to level i. Average population density of excitation state N_i level can be determined by considering that plasma is optically thin for all emission lines using the relation [9]

$$N_i = \frac{4\pi I_{ij}}{h\nu_{ij} A_{ij} L} \quad , \qquad (3)$$

where $h\nu_{ij}$ and L are the energy gap between ground to higher level and average plasma length that the emitted light collected along the line of sight through optical fiber, I_{ij} is absolute intensity measured by power meter and A_{ij} and k_{1i} are taken from NIST database. We have used the strong lines of Ar (750.4 nm and 763.5 nm) and hydrogen (Hα (656 nm) and Hβ (486 nm)) to estimate the density of plasma under study using Eqs. (1), (2), and (3).

Figure 3 shows the comparison of variation in the plasma parameters T_e and N_e estimated by OES and LP for Ar and H_2 plasma. It is inferred from Fig. 3 (a) and (b) that with increase in pressure, T_e decreases in both Ar and H_2 plasmas. We observed that T_e is little higher for hydrogen plasma as compared to Ar plasma at same experimental input parameters. The small difference in T_e in the two cases, LP and OES measurements may be explained as follows. LP measurements give local information of plasma and OES method gives average line integrated values along the plasma length where local plasma parameter values could be varying along the length (lower as well as higher).

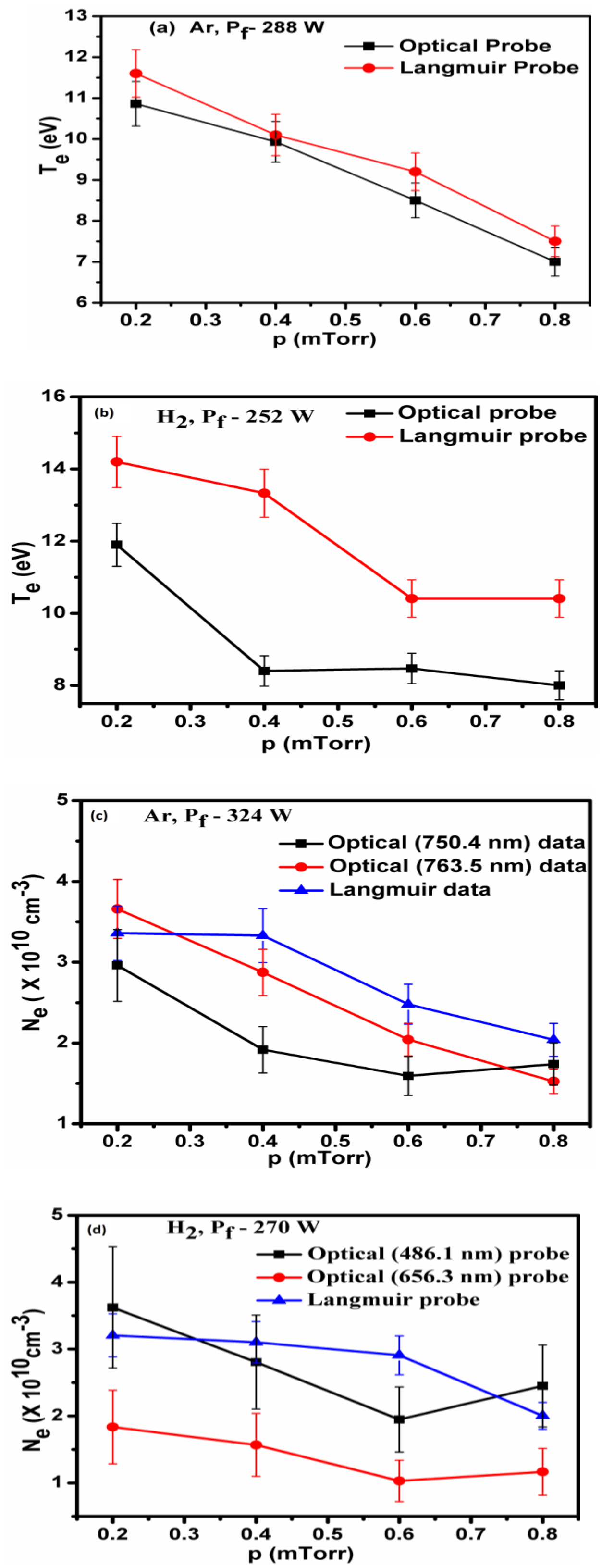

Fig 3. Comparison of OES and LP for T_e with p variation, (a) at constant forward power (P_f) 288 W for Ar plasma, (b) at constant P_f 252 W for H_2 plasma. N_e with p variation, (c) at constant P_f 324 W for Ar plasma and (d) at constant P_f 270 W for H_2 plasma.

The pressure dependence of the electron density (Fig. 3(c) and (d)) reveals that the increase in pressure decreases the electron density. Because as background pressure goes further down, the life time of the lines emitted from upper level states thereby decreases, the population density at higher states from line causing the decrease in intensity. The intensity reduces with increase in pressure, lower the electron density (Ref. Eq. 3).

5. Conclusion

The intensities of the Ar and Hydrogen lines are investigated at pressures in the range of 0.2 to 0.8 mTorr. We observed reasonably close agreement between Langmuir probe and optical emission spectroscopy results for N_e and T_e. Two different emission lines for both Ar and H_2 gases are chosen for plasma density measurements. We conclude that based upon the OES, strong lines from Ar plasma are 750.4 nm, 772.0 nm, 811.5 nm and H_2 plasma are 656.3 nm and 486.1 nm. Scanning for these strong lines is carried out in the tomographic measurement system.

6. References

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