Paper

Influence of N_2 Seeding on the Ignition Dynamics of High Pressure RF Ar Inductive Discharges

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Abstract

The influence of nitrogen (N_2) seeding on the ignition dynamics of high pressure (0~50 kPa) radio frequency (rf) Argon (Ar) inductive discharges in a moderate rf power of about 2~10 kW is investigated experimentally. The discharge is sustained in a Pyrex glass chamber by using a high power SIT (Static Induction Transistor) inverter power source. High speed camera imaging is performed to observe the ignition dynamics of Ar and Ar-N_2 rf discharges. The experimental observations reveal that higher threshold current (power) and longer initiation time is required to ignite the high pressure Ar-N_2 plasmas, with a 2.5~10% N_2 seeding, than that of pure Ar plasmas with the same operating conditions. It is also noticed that the ignition dynamics of high pressure rf discharges can also be observed from the generated plasma loading impedance and absorbed power.

Keywords: inductively coupled plasma, ignition dynamics, high speed imaging, plasma loading impedance

1. Introduction

By taking the advantages of high temperature and high energy, high pressure rf inductive discharges have achieved significant importance over the last few decades for various industrial applications [1-6] such as material processing, spray coating of metals and ceramics, deposition of diamond films, disposal of harmful gases and waste materials destruction. A feature of most of these applications is that mixtures of different gases are used [7-10], such as, in plasma spraying Nitrogen (N_2), Helium (He) or Hydrogen (H_2) is typically added to Argon (Ar). The selection of these plasma gases is primarily based on the gas energy, reactivity, cost and applications of the generated plasmas. N_2 gas has the high internal energy over Ar and He due to the dissociation reaction in the N_2 prior to ionization [11]. The low cost and high internal energy of N_2 make it one of the most useful discharge gases to generate induction thermal plasmas. But to generate pure N_2 thermal plasmas at high pressure, large power is required due to high power consumption for the formation of molecular ions N_2^+ and dissociation of N_2 molecules [7, 12]. One solution to solve this problem is to add Ar with N_2 to produce Ar-N_2 mixture thermal plasmas. Therefore, the motivation of this work is to investigate the effect of adding the N_2 on pure Ar inductive discharges at the ignition stage, and thus to investigate the effect of E-H mode transition time [13].

2. Experimental Setup

The schematic of experimental setup is depicted in Fig.1. In the present experiment, an SIT inverter power source [14] with a frequency range of 0.2~2.0 MHz and maximum output power of about 20 kW is employed to generate Ar induction thermal plasmas in atmospheric pressure. An induction coil consisted with 7 turns of a copper tube of 1/4 inch outer diameter is used as the loop antenna. The plasmas are sustained in a cylindrical Pyrex glass chamber with an internal diameter of 70 mm and length of 200 mm. Ar gas, whose pressure is controlled by using a mechanical rotary pump, is injected both in axially and swirly into the torch vessel with a total flow rate of 20~30 litter/min. The neutral gas pressure is measured with a total pressure gauge. The rf power level, which is limited by the cooling capability of the system, is modulated with a 100 msec square wave pulse (extended up to 5 sec). Repetitive spark discharge, using the spark discharge technique [15], with a repetition frequency of 500 Hz and duration of 30 ms is applied simultaneously with the rf pulse to initiate the discharge. This task is performed by using a simple automobile spark plug, placed at the center of the top flange of the vacuum chamber (shown in Fig.1), with a high voltage transformer circuit. A matching network is employed to optimize the plasma loading impedance and power coupling efficiency. A '*FASTCAM-ultima SE*' high speed camera with a frame speed of 4500~13500 f/s is used to investigate the ignition dynamics.

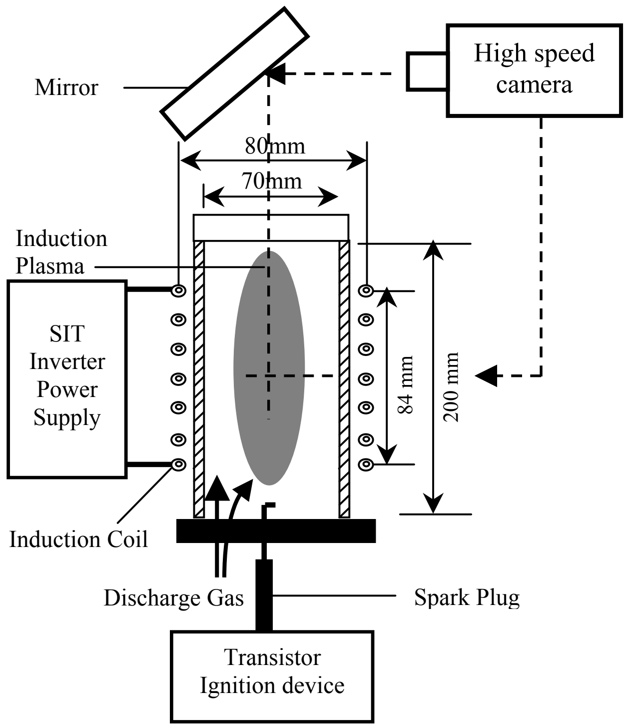
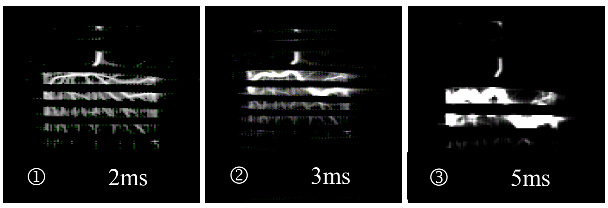


Fig.1: Schematic of experimental setup

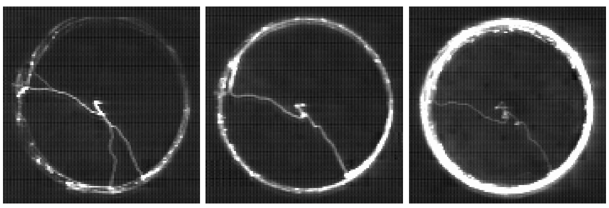
3. Ignition Dynamics: Experimental Observation

The ignition dynamics of rf inductive discharges observed by the high speed imaging can briefly be described as follows: At the starting of ignition, highly mobile electrons are accelerated and picked up energy from the applied electrostatic field, $\widetilde{E}_z$, the average intensity of which is high enough (in the present experiment ~120 kV/m) to excite and ionize the working gas thereby developing the multiple streamer-like discharge paths (E-discharge) at the top of the torch chamber and very close to the inner surface of the discharge chamber [Fig.2 (a) ① and 2(b)(i)] due to the stronger E_z near the torch surface. Then, the discharge paths connect among the streamers due to the induced electric field, $\widetilde{E}_\theta$ (in the present experiment ~2.5 kV/m). But, the electron energy gain by the induced electric field is not high enough to ionize the working gas. At this stage, collisional heating occurs due to the strong axial electrostatic field, which gives enough energy to the electrons. The induced azimuthal electric field promotes diffusive motion for electrons in the azimuthal direction. These energetic electrons produce ionization and make electrically conducting bridges between the neighboring streamers by the diffusive process and transform the streamers into the ring-shaped azimuthal (H) discharge paths [Fig.2 (a) ②, ③ and 2 (b)(ii)]. The conductive ring makes it possible to induce the azimuthal current and to inject the Joule power into the ring-shaped plasma. For the time being the H-discharge develops downward thereby forming the steady state plasmas [Fig.2 (b)(iii)] due to Joule heating with the azimuthal rf current. From Fig.2 (b), it is seen that the discharges develop near the inner surface of the discharge vessel because of the stronger E_θ near the torch surface.

From the experimental observation by fast camera imaging, the E-H discharge mode transition time is found to be about 500 ~ 1000 μs. This mode transition time can also be observed from the temporal plasma loading impedance, which we will be described latter in section 4.



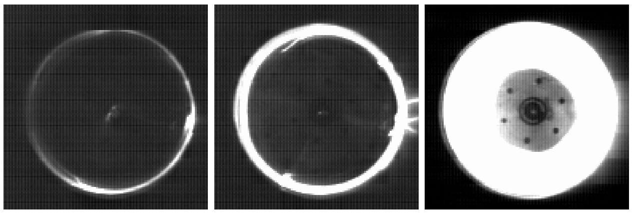
(a) Side view



(i) 2ms (ii) 3ms (iii) 5ms

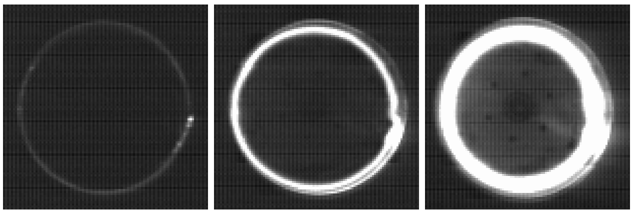
(b) Top view

Fig.2: Observation of ignition dynamics by high speed imaging



① 1.0 ms ② 1.7 ms ③ 4.0 ms

(a) Ar plasma



① 1.1 ms ② 2.3 ms ③ 4.0 ms

(b) Ar-N_2 plasma

Fig.3: Temporal discharge development at 20 kPa

4. Plasma Loading Impedance

Since the plasma heating mechanism is essential for high pressure induction plasmas, and the plasma resistance is the crucial quantity for heating mechanism and power coupling in induction plasma, we measure the temporal plasma loading impedance (both resistance and reactance) at the ignition stage to investigate the ignition dynamics of Ar and Ar-N_2 rf inductive discharges. The loading impedance looking from the primary circuit (Fig.4) is given by

$$z_1 = R + jX = \frac{v_{rf1}}{i_{rf1}} \quad \text{---------------} \quad (1)$$

where, v_{rf1} and i_{rf1} are the primary circuit rf voltage and current, respectively, R is the total circuit resistance and X is the circuit reactance. Therefore, the plasma loading impedance can be calculated by the transformer turn ratio, a as

$$z_z = a^2 z_1 \quad \text{---------------------} \quad (2)$$

with $a = n_2/n_1$, where n_1 and n_2 are the number of turns of the transformer in the primary and secondary side, respectively.

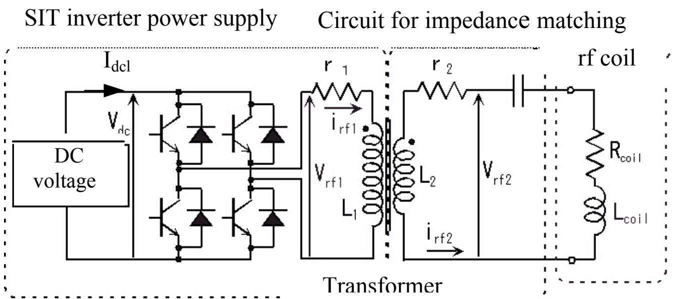


Fig.4: Equivalent circuit diagram of SIT inverter power supply and rf induction coil

Fig.5 and 6 shows the temporal plasma loading resistance and reactance, respectively, calculated by the inverter output voltage and current [equation (1) and (2)]. The respective resistance and reactance of the discharge development of Ar and Ar-N_2 (2.5% N_2) plasmas shown in Fig.3 are indicated by the timing ①, ② and ③ in Fig.5 and 6. It is noticed that the plasma loading resistance at the starting of ignition i.e. in the E-discharge region remains almost constant and is not high enough for plasma heating. But, the increment of loading impedance changes remarkably after the E-H mode transition i.e. in the region of the development of H-discharge and again remains almost constant in the steady state region as shown in Fig.5. On the other hand, the loading reactance of the generated plasmas is relatively high in the E-mode due to the development of streamer like discharges by the capacitive coupling between plasma and rf power. The reactance decreases after E-H mode transition, since the streamers disappear in this region, an electrically conducting ring is formed and consequently, the loading resistance is increased. However, the loading reactance of Ar-N_2 plasmas in the steady state H-mode is higher than that of pure Ar plasmas as shown in Fig.5.

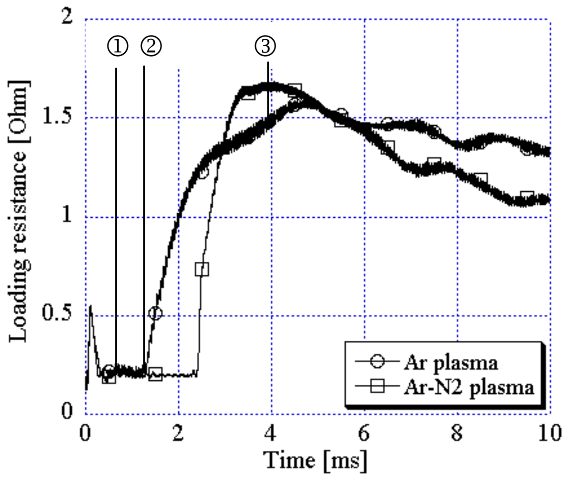


Fig. 5: Plasma loading resistance

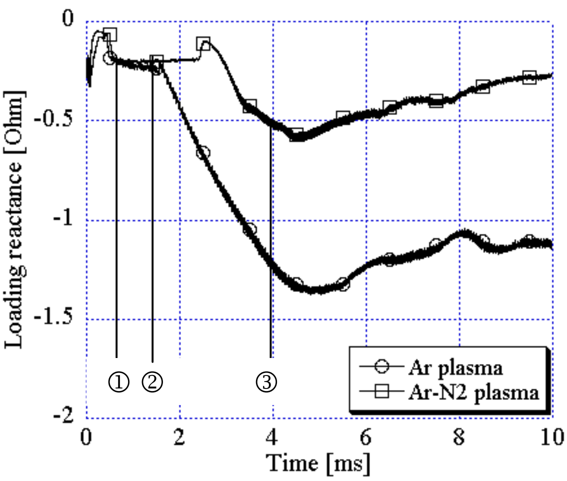


Fig. 6: Plasma loading reactance

The development of E-discharge, E-H mode transition, development of H-discharge and finally the formation of steady state thermal plasmas can be seen clearly from the dynamic plasma loading impedance (resistance and reactance) since the slop of the curve changes at every mode as shown in Fig.5 and 6. The gross E-H discharges transition time (which is determined by the various factors such as ionization, Joule heating, loss mechanisms etc.) for Ar plasma generated in a neutral pressure of 20 kPa and rf power of about 2 kW is found to be about 600~700 μs, while for Ar-N_2 (2.5% N_2) plasma is about 1.2~1.3 ms with the same operating conditions. In the present experiment, the vacuum resistance i.e. the loading resistance without plasma, the loading resistance of E- and H-discharge of Ar induction plasma in a pressure of 20 kPa are found to be about 0.17, 0.18~0.2 and 0.2~1.5 ohm, respectively.

The plasma loading impedance (including resistance and reactance) of Ar and Ar-N_2 (5% N_2) plasmas in a pressure of 40 kPa, calculated from the dc input voltage and current (see Fig.4), is shown in Fig.7. It can be mentioned from Fig.7 that there will no growth of loading impedance be found if there is no development of H-discharge in the case of Ar-N_2 (5% N_2) plasma, because the H-discharge failed to be maintained due to an imbalance between the input energy gain and the strong radiative energy loss due to high enthalpy nitrogen gas content. This will be discussed in another paper.

It is observed that the plasma loading impedance (both reactance and resistance) oscillates after the E-H mode transition both in the case of Ar and Ar-N_2 plasmas. These oscillations, probably, come from the non-uniform growth of the plasma, and this non-uniformity decreases with time.

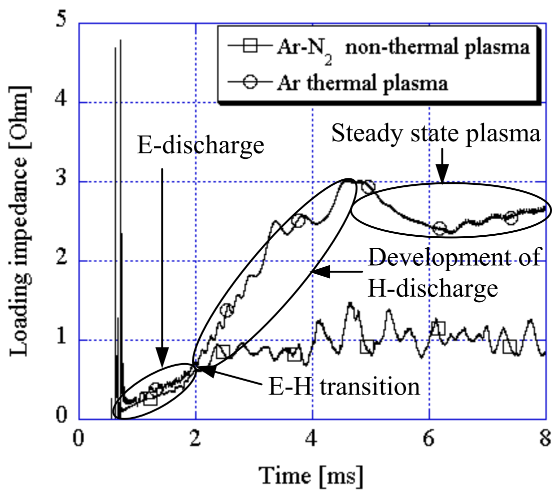


Fig.7: Temporal plasma loading impedance at the ignition stage

5. Conclusion

The influence of N_2 seeding on the ignition dynamics of Ar inductive discharges has been investigated experimentally. High speed camera imaging is performed to investigate the ignition mechanism. It is noticed that the ignition dynamics including the E-H discharge mode transition can be investigated from the dynamic plasma loading impedance (resistance and reactance). The percentage of N_2 seeding clearly affect on the initiation time, plasma loading impedance and consequently, on the E-H mode transition. With higher N_2 seeding, plasma initiation time and thus the E-H discharge mode transition time become higher and vice versa, with the same operating conditions. This means that plasma losses become higher with increasing the percentage of N_2 seeding on pure Ar plasma.

Acknowledgement

The authors would like to express their sincere gratitude and thanks to the cooperation program committee of NIFS (National Institute for Fusion Science), Japan to provide the 'FASTCAM-*ultima* SE' camera during the experiment.

References

(1) M. I Boulos, P. Fauchais and E. Phender. *Thermal Plasmas: Fundamentals and Applications*. Plenum press, New York and London, 1994.

(2) Thomas B. Reed. *Journal of Applied Physics*, Vol. 32, No. 12, p. 2534, 1961.

(3) Toyonobu Yoshida, Toshihiko Tani, Hirobumi Nishimura and Kazuo Akashi. *Journal of Applied Physics*, Vol. 54, No. 2, p. 640, 1983.

(4) S. Xu, K. N. Ostrokov, Y. Li, E. L. Tsakadze and I. R. Jones. *Physics of Plasmas*, Vol. 8, No. 5, pp. 2549-2557, 2001.

(5) C. H. Cruger, T. G. Owano, C. O. Laux and R. N. Zare. *Journal of Physics IV*, Vol. 7, 1997.

(6) J Reece Roth. *Industrial Plasma Engineering - Volume 2: Applications to Nonthermal Plasma Processing.* Institute of Physics Publishing, Bristol and Philadelphia, 2001.

(7) K. C. Paul and T. Sakuta. *Electric Power Systems Research*, Vol. 56, Issue 3, pp. 185-193, 2000.

(8) M. Desilets, B. Davies, G. Soucy and P. Proulx. *Canadian Journal of Chemical Engineering*, Vol. 76, pp. 707-716, 1998.

(9) M. M. Hossain, Y. Hashimoto, Y. Tanaka, K. C. Paul and T. Sakuta. *IEEE Transactions on Plasma Science*, Vol. 30, No. 1, pp. 327-337, 2002.

(10) A. B. Murphy. *Journal of Physics D: Applied Physics*, Vol. 34, pp. R151-R173, 2001.

(11) D. A. Gerdeman and N. L. Hecht. *Arc Plasma Technology in Material Science.* Springer-Verlag, Wien and NY, 1972.

(12) K. Ostrikov, E. Tsakadze, J. Ning, Z. Tsakadze, L. Jidong, R. Storer and S. Xu. *IEEE Transactions on Plasma Science*, Vol. 30, No. 1, pp. 128-129, 2002.

(13) M. A. Razzak, K. Kondo, Y. Uesugi and S. Takamura. *Conference Record of 2003 IEEE International Conference on Plasma Science (ICOPS 2003)*, 2~5 June, 2003, Lotte Hotel Jeju, Jeju, Korea, p.446.

(14) Shinichi Watanabe, Yoshihiko Uesugi, Shigeyuki Ohsawa and Shuichi Takamura. *Review of Scientific Instruments,* Vol. 69, No. 10, pp. 3555-3557, 1998.

(15) Y. Uesugi, T. Adachi, K. Kondo and S. Takamura. *Transactions of the Institute of Electrical Engineers of Japan*, Vol. 122-A, No. 5, pp. 461-466, 2002. (In Japanese)

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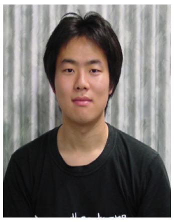

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