Paper

Transient Behaviors of Radio Frequency Inductive Discharges in Atmospheric Pressure

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Abstract

The dynamic behaviors of radio frequency (rf) discharges using inductively coupled plasma (ICP) technique in atmospheric pressure are investigated experimentally. From the experimental investigation, a rapid increase of the coil loading resistance and decrease of the effective coil inductance are observed during the dynamic change of plasma from electrostatic (*E*) to electromagnetic (*H*) mode. The phase and frequency shift from their resonance value during the load changes from the *E* to *H* mode. As a result, the rf coil current drops abruptly, thereby decreasing the effective absorbed rf power and thus the plasma production efficiency. By controlling the gate driving frequency shows successful improvement of the power efficiency.

Keywords: inductively coupled plasma, frequency tracking, power efficiency, radio frequency

1. Introduction

Inductively coupled plasma (ICP) technique is one of the methods to generate radio frequency (rf) discharges. The concept of ICPs are not new and its generation [1-3], modelling [4,5], characterization [6,7], processing [8,9] and applications [10,11] have been reported in many literatures since the last few decades with the intention of achieving each goal. Although the concept of induction heating was first introduced by Hittorf in 1884 [1], the full concept of induction plasmas and their applications were reported by Reed in 1961 [2, 3], and after that a lot of works were conducted by the scientists and researchers all over the world to provide these plasma reactors in the several fields of applications. But, most of these researches were conducted for the low-pressure ICPs, since the initiation, generation and diagnostics of the low-pressure ICPs are easy. On the other hand, there has been increasing the interest in the potentiality of high-pressure induction plasmas during the past decades in a diversity of researches because of its high temperature and high reaction activity, and wide range of applications such as material processing, spray coating of metals and ceramics, thin films deposition, waste materials destruction, and disposal of harmful gases (NOx, CO_2, O_3, CFC etc.) that are responsible for global worming and environmental pollution.

However, so far, attention has been drawn on heating, sustainment, stabilization and applications of rf induction plasmas. But, when operated at high pressures (ar ound 1 atm or more), initial start-up is one of the important issues to ignite the discharge of induction plasmas, since the starting of high-pressure rf plasma torches are hard, and a high-voltage initiation is usually required [11]. So far several techniques, such as, dc arc jet and rf-hybrid plasma torch are used to initiate the high-pressure rf inductive discharges. But, these hybrid plasma torches characteristically operate at power levels of 50 to 100 kW or even more, where the dimensions of the second- stage, high-power unit make it difficult to initiate and operate in a stable manner. But to promote induction plasmas into industrial and commercial fields, it is customary to make it cost effective with as low power as possible especially where the power is limited. Therefore, it is necessary to understand the physical mechanisms of the formation of high-pressure induction plasmas, which are quite different with that of the low-pressure plasma dynamics. With those in mind, we have studied the dynamic behaviors of atmospheric pressure argon induction inductive discharges at the ignition stage experimentally, to investigate the dynamics of physical processes and initial formation of rf discharges in a frequency of 1.2 MHz and a moderate rf power of about 4-5 kW.

High-power transistors such as static induction transistor (SIT)-based inverter power source has become popular in the last decade with its application to various kinds of induction heating and plasma generation [12-17] due to their high-efficiency and high-power operation. However, at high operating frequencies in the MHz range, rf system behaves transient and strongly non-linear due to the presence of switching devices in the power source and non-linear interaction between plasma and rf source. Inherent problems are, therefore, observed in the SIT inverter power source during high-pressure induction plasma generation [15-17]. With those in mind, in this article we investigate the dynamic behaviors of radio frequency (rf) inductive discharges at the ignition stage generated by inductively coupled plasma (ICP) technique in atmospheric pressure.

2. Experiment

The schematic diagram of experimental setup is depicted in Fig. 1(a). The inverter DC input voltage and current, rf output voltage and current, and rf coil current and voltage are measured to analyze the dynamics behaviours of generated plasmas. The plasmas are sustained in a cylindrical Pyrex glass chamber with an internal diameter of 70 mm and length of 200 mm by applying a static induction transistor (SIT) inverter power source, the equivalent circuit of which along with rf induction coil is shown in Fig. 1(b). The rating of frequency range and maximum output power of the SIT inverter is 0.2–1.7 MHz and 20 kW, respectively. An induction coil consisting of seven turns of a copper tube of ¼ inch outer diameter is used as the loop antenna. Ar gas is injected both axially and spirally into the torch vessel with a total flow rate of 20 lpm. The neutral gas pressure is measured with a total pressure gauge by using a mechanical rotary pump. The rf power level, which is limited by the cooling capability of the system, is modulated with a 100 ms square wave pulse without applying any cooling system. Repetitive spark discharge, using the spark discharge technique [14], with a repetition frequency of 500 Hz and duration of 20–30 ms, is applied simultaneously with the rf modulating pulse to initiate the discharge. This task is performed by using a typical automobile spark plug, placed at the center of the top flange of the discharge chamber with a high-voltage transformer circuit as shown in Fig. 1(a). An *LC* matching network is employed to optimize the power coupling efficiency. A "FASTCAM *ultima* SE" high-speed camera with a frame speed of 13500 fps is used to observe the mode transition dynamics. The side-view images are taken by setting the camera perpendicular to the axis of the discharge chamber, while the end-views are taken by setting a mirror on the bottom of the discharge chamber inclined 45^0 to that of the discharge axis as shown in Fig. 1(a).

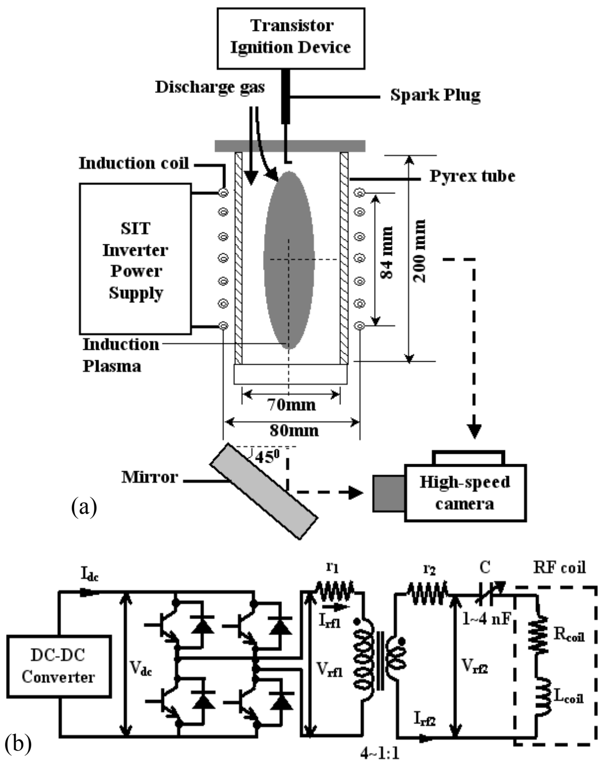

Fig.1 Schematic diagram of experimental setup (a), equivalent circuit of SIT inverter and rf coil (b). One of the six SIT inverter units is shown in Fig. (b).

3. Dynamic Behaviors

A typical radio frequency (rf) inductive discharge is usually generated by applying rf power, with conventional series resonance circuit, in an inert gas chamber (Ar, He etc.) wound with an induction coil of a few turns [14-16]. At the initial phase of rf breakdown, a streamerlike electrostatic discharge or *E* discharge [Fig.2 (a), (b)] develops by the strong axial electrostatic field (100-200 kV/m) due to the high rf voltage on the induction coil for several hundred microseconds, and then a rapid transition from electrostatic to electromagnetic mode occurs developing the ring-shaped electromagnetic discharge or *H* discharge [Fig.2 (c)] to form the volumetric induction plasmas [Fig.2 (d),(e)]. A rapid increase of the coil loading resistance and decrease of the effective coil inductance are observed during these dynamic mode changes of the generated plasmas as shown in Fig. 3. The load of the SIT inverter, which is resistive without plasma due to a resonance tuning, becomes inductive in the *E* mode while slightly capacitive in the *H* mode. This will be discussed in next paragraph.

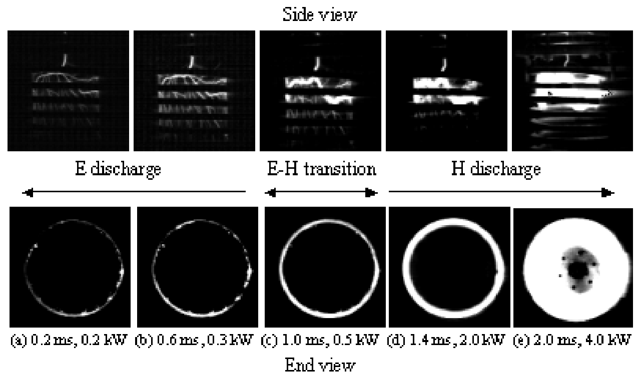

Fig. 2 Observation of ignition and *E-H* mode transition dynamics in atmospheric pressure argon plasma. The timing and corresponding rf power are indicated below the respective image. The time indicated in the figure is calculated after starting the initiations.

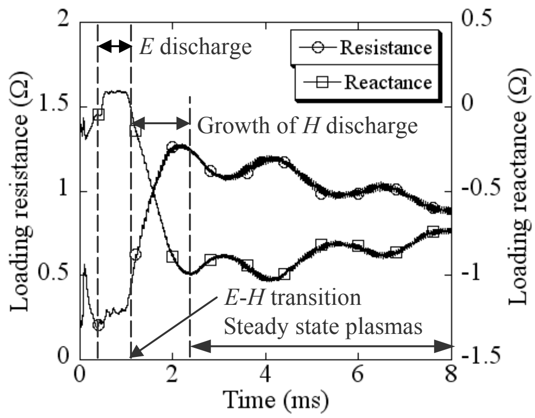

Fig. 3 Temporal plasma loading impedance at the ignition stage showing the different modes of operation

The temporal behavior of plasma loading impedance (both real and reactive part), obtained by the rf input voltage to current ratio, indicating a dynamic transition from one mode to another is shown in Fig. 3. The resistance in the *E* mode is very small due to a weak coupling of streamerlike discharge and becomes high in the *H* mode due to the growth of the inductive plasma. The rf coil current, therefore, drops abruptly, as shown in Fig. 4, when the load changes from the capacitive to inductive mode due to the impedance rise thereby decreasing the absorbed rf power and thus the power coupling efficiency [14].

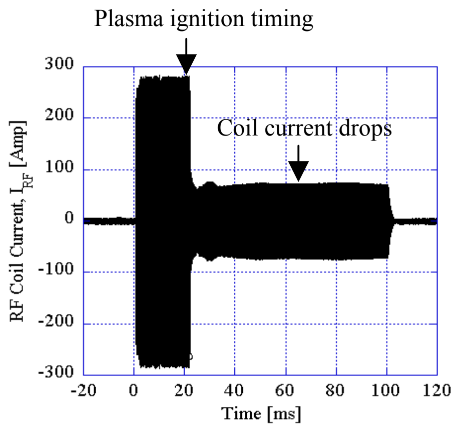

Fig. 4 RF coil current at the time of plasma ignition

The reactance, on the other hand, is slightly positive in the *E* mode, and decreases and becomes negative with the development of the *H* mode due to plasma reaction by the induction current, which flows in the azimuthal direction but opposite to that of the rf coil current, thereby decreasing the effective coil loading inductance. As a result, the phase and driving frequency is shifted from their resonance value during the *H* mode as shown in Fig. 5 and 6, respectively. The total load, therefore, becomes slightly capacitive during the *H* mode thereby increasing the switching losses of the SIT inverter elements. As a result, the inverter output power is decreased, thereby decreasing the dc–rf conversion efficiency of the SIT inverter from about 90% to 40% as shown in Fig. 5.

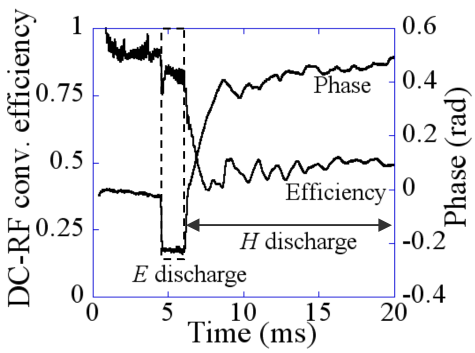

Fig. 5 Time behavior of phase and dc-rf conversion efficiency during *E*-*H* mode transition

4. Enhancing the Power Efficiency

The dc–rf conversion efficiency of the SIT inverter power source can be enhanced by applying the immittance conversion circuit [17], which helps to inject a high effective rf power to the plasma than the conventional series resonance circuit. In this experiment, we use another simple and robust method by controlling the gate driving frequency, changing it from 1120 to 1250 kHz starting at about 40 ms when the *E* mode has been transferred to *H* mode. However, the experimental conditions other than the frequency control remain unchanged. The temporal change of the gate driving frequency from 40 to 60 ms is shown in Fig. 6, and the effective rf power and dc–rf conversion efficiency are shown in Fig. 7. Figure 7 shows that the rf power becomes double from about 3.5 kW to 7 kW, thereby enhancing the dc–rf conversion efficiency from about 40% to 85% by bringing the driving frequency close to resonance one. This is because by controlling the driving frequency close to resonance value, the losses mainly coming from the switching devices present in the inverter circuit are considered to become low, thereby increasing the rf output power and thus the dc–rf conversion efficiency of the SIT inverter power source.

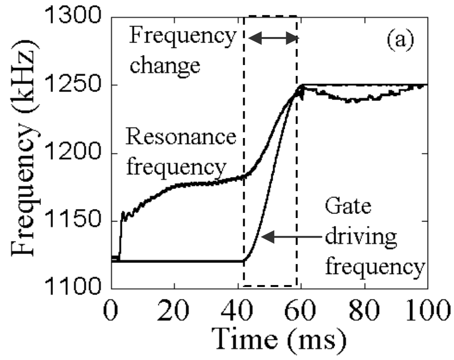

Fig. 6 The evolution of the driving and resonance frequency

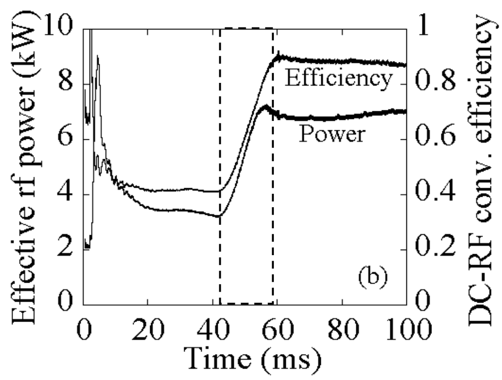

Fig. 7 DC-RF conversion efficiency of the SIT inverter when the driving frequency is varied as shown in figure 5

5. Conclusion

The transient behaviors of radio frequency argon inductively coupled plasmas in atmospheric pressure are investigated experimentally. The experimental observations reveal that, a rapid increase of the effective coil loading resistance and decrease of the inductance occurs during the dynamic change of plasma from electrostatic to electromagnetic mode. The total load of the SIT inverter, which is resistive without plasma due to a resonance tuning, becomes inductive in the *E* mode while slightly capacitive in the *H* mode, thereby increasing the switching losses of the SIT inverter elements. As a result, the inverter output power is decreased, thereby decreasing the dc–rf conversion efficiency of the SIT inverter from about 90% to 40% as shown in Fig. 5. However, the conversion efficiency can be enhanced from about 40% to 85% by performing the frequency control as shown in Fig. 7.

Acknowledgements

The authors would like to express their sincere gratitude and thanks to NIFS (National Institute for Fusion Science), Japan for the cooperation in providing the "FASTCAM *ultima* SE" high-speed camera during the experiments. They also thank to Dr. Ohno for his thoughtful and helpful comments, and to Mr. Takagi for his technical assistance during the experimental setup.

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