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Recent Advance in High Pressure Induction Plasma Source

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Abstract

An induction thermal plasma system have been newly designed for advanced operation with a pulse modulated mode to control the plasma power in time domain and to create non-equilibrium effects such as fast quenching of the plasma to produce new functional materials in high rate. The system consists of MOSFET power supply with a maximum power of 50 kW with a frequency of 450 kHz, an induction plasma torch with a 10-turns coil of 80 mm diameter and 150 mm length and a vacuum chamber. The pulse modulated plasma was successfully generated at a plasma power of 30 kW and a high pressure of 100 kPa, with taking the on and off time as 10 ms, respectively. Measurements were carried out on the time-dependent spectral lines emitted from Ar species. The dynamic behavior of plasma temperature in a pulse cycle was estimated by the Boltzmann plot and the excitation temperature of Ar atom was found to be changed periodically from around 0.5 to 1.7 eV during the cycle. Two application regions of the induction thermal plasma newly generated were introduced to material processing with high rate synthesis based on non equilibrium effects, and to the finding of new arc quenching gases coming necessary for power circuit breaker, which is friendly with earth circumstance alternative to SF6 gas.

1. INTRODUCTION

Over the past several decades, a large effort has been devoted to the experimental and numerical analysis of the temperature or the flow fields in the inductively-coupled r.f. (radio frequency) plasma in the steady state, continuos mode. In conjunction with respects to the application of such thermal plasma with a high reactivity to the processing of materials, a special attention has been given recently for the investigation about the dynamic behavior of the induction plasma. Sakuta et al[1, 2] developed first a 1-dimensional model to study the dynamic behavior of r.f. induction thermal plasma to a sudden change in coil current, and then the 2-dimentional time dependent code has been developed by Mostaghimi et al[3]. Both calculations showed almost equivalently that the time required to achieve a new steady-state was around 5 to 30 ms for the pressure range from 10 to 100 kPa. This means that if the absent time of the exciting magnetic field is less than the above time constant, the plasma will reestablished again by a pulse on action in the sustaining electromagnetic field. This feature gives an interesting possibility to introduce several important effects in the high-power and high-pressure inductively coupled thermal plasma, that is, 1) Repetitive generation of high and low temperature period, 2) Control of power and heat flux in time domain, 3) Application of extremely high or low electromagnetic field, 4) Introduction of non-equilibrium condition in the electron and heavy particles temperatures as well as in the composition of chemical species including an emphasis of important radicals.

In this paper, an induction thermal plasma system have been newly developed for the advanced material processing with introducing the pulse modulation mode, which may create non-equilibrium effects in high pressure thermal plasmas. After explanation of the new power transistor system with 50-kW power and 450-kHz frequency MOSFET (Metal Oxide Semiconductor Field Effect Transistor), experimental results are presented for successful operation with pulse modulated mode at a plasma power of 30 kW and a pressure of 760 torr. Dynamic change of the plasma temperature during a pulsing cycle was measured by optical emission spectroscopy and the results showed a strong deviation from the LTE (Local Thermal Equilibrium) calculation. Two potential application regions were introduced and explained for 1) material processing with using emphasized non equilibrium effects, and 2) development of new quenching gases for arc interruption in circuit breakers with using time-dependent characteristic of the pulsed induction plasma. Discussions were made on the concept of pulsation lying behind, with a comparison of pulse modulation technique frequently appears in the cold plasma region.

2. Principle of Pulse Modulation

In order to achieve the pulse modulation of the magnitude of the coil current oscillating with a high frequency around MHz, the solid state transistor devices are necessary to be introduced newly, rather than the conventional vacuum tube oscillator technique. The applicable region of the semiconductor inverter with respects to the power and the frequency has been developed and extended in electronics industry. Among several high power transistor device appears in the commercial stage, MOSFET (Metal Oxide Semiconductor Field Emission Transistor) or SIT (Static Induction Transistor) is most promised candidate for our trial of generating the pulse-modulated induction thermal plasma, because the applicable range of the frequency high as 500 kHz, which is within the range capable of exciting the gaseous medium in a conductive plasma state. Fig. 1 shows a comparison of two coil currents of in normal continuous mode and in pulse modulated mode. In the normal mode shown in Fig. 1 (a), Since the amplitude of the coil current is constant and the characteristic time constant of the thermal plasma of ms order is much larger the than the period of 2(s which corresponds to 450 kHz, an inductively coupled plasma behaves just like as rigid metallic medium which exhibits a continuous steady aspect. However, in the case of Fig. (b) where the pulse modulation is adopted in the amplitude of the coil current with a cycle of 10 ms order, the plasma should have a transient behavior corresponding to the pulse on and off action, because the period of the pulse disturbance is as long as the plasma can follow it[2, 3]. By controlling the duty factor and the current ratio in the pulse on and off period, new feasibility and effects are expected to the high-power thermal plasmas. The principle limitation of such pulse modulation of the induction thermal plasma was recognized already in both the theory and experiment, in terms of maximum pulse off time of around 20 ms, beyond which the plasma diminishes due to the lack of the electrical conductivity[4].

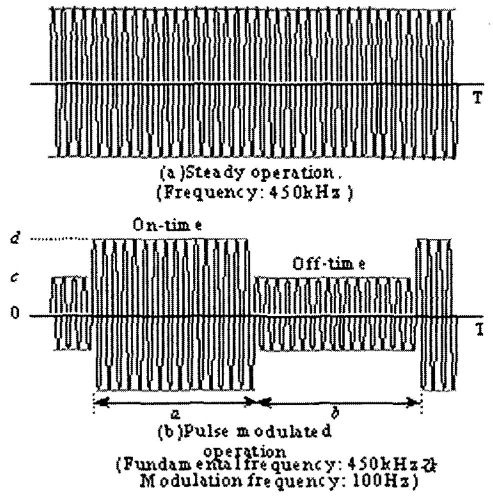

Fig. 1 Principle of Pulsation in Induction Plasma

3. Pulse modulated Induction Plasma System

An induction thermal plasma generation system was developed, which can be operated with both continuous and pulse modulated mode. A new system has a MOSFET inverter power supply which has a rated power of 50 kW at a fundamental frequency of 450 kHz with a high conversion efficiency more than 85 %. The induction plasma torch shown in Fig. 2 consists of a 10-turns coil of 130-mm diameter and 155-mm length, which is considerably large for both radial and axis dimensions compared to the conventional torches associated with the vacuum tube power supply.

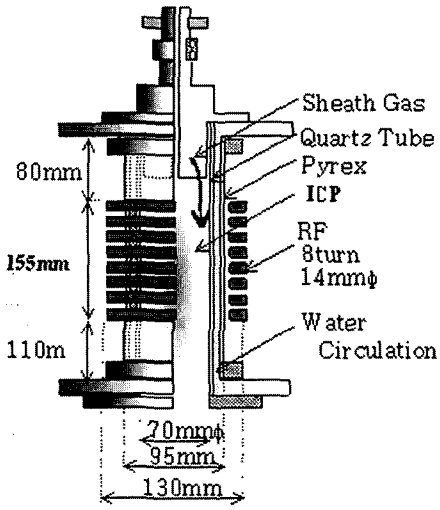

Fig. 2 Schematic of Induction

The main plasma torch has a standard construction of double quartz tubes and the inner one has 70-mm diameter and 370-mm axial length. The transmission of electrical power from the inverter to the plasma is made by a series LC resonance circuit rather than the parallel resonance circuit. This is mainly reflected by the rated output of 150-V voltage and 460-A current of the inverter. After the successful operation in the usual continuous mode, the pulse mode operation was performed at a power level of 30 kW for Ar-H2 plasma under atmospheric pressure condition, whose photograph is shown in Fig. 3. The actual waveforms of the time-dependent pulsing signal installed in the control unit and the modulated magnitude of coil current are shown in Fig. 4 for the pulse period of 15 ms.

The lower level of the current magnitude reaches down to 40 % of the maximum, which corresponds to 16 % in plasma power level. The rise and fall time of the current magnitude was around several hundreds (s. This is much shorter than the inherent time constant of the induction

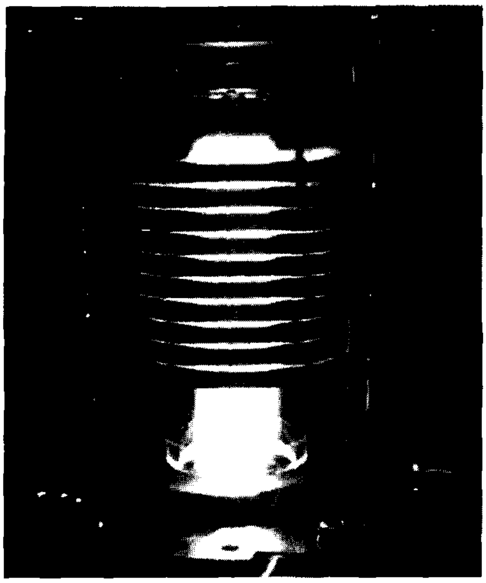

Fig. 3 Photograph of Pulsed Induction Plasma

plasma, several ms. Thus, the system developed gives almost ideal pulsing action against the plasma, which is necessary especially for generating the non-equilibrium effects in the plasma, or for measuring the inherent dynamic behavior of the plasma.

4. Two Application Regions of Pulse Modulated Induction Plasma

The pulse modulated induction plasma at a high pressure condition developed above is considered to have a potential application to two technical regions at this stage. First is for new material processing with high rate synthesis based on non-equilibrium effects, which can not be achieved with the low temperature cold plasma. The main advantages of the method are 1) time-domain control of heat and particle fluxes toward the substrate where the processing is made, and 2) an introduction of non-equilibrium condition in

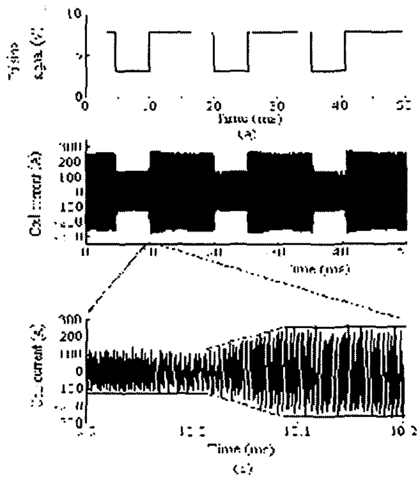

Fig. 4 Waveform of Pulsed High Frequency Coil Current

the electron and heavy particles temperatures as well as in the composition of chemical species such as radicals. The second application region is for new arc quenching gases necessary to high power circuit breaker, which should be friendly with earth circumstance alternative to SF6 gas. In this case, the time-dependent characteristics of pulsed induction plasmas including candidate gases (N2, O2, Air, CO2 etc.) is useful to determine the inherent time constant with respects to the plasma quenching, that is, interruption process of high pressure arc plasma.

4. 1 High Rate Plasma Processing Associated with Non-Equilibrium Effects

In order to investigate the transient properties of induction thermal plasma thus pulsated, optical emission spectroscopy was used for determine the plasma temperature as well as particle number density which change periodically within the pulsing cycle. The measurement system is consisted of an optical lens and a monochromator (Jo-

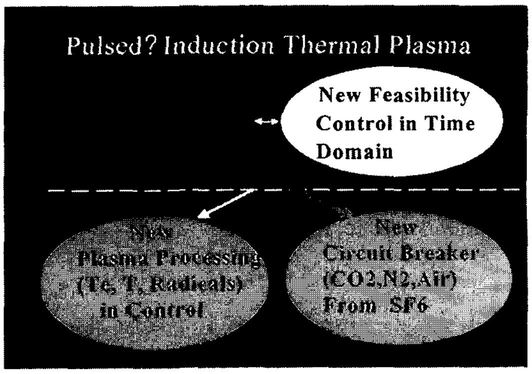

Fig. 5 Application Region of Pulsed Induction Thermal Plasma

bin Yvon HR-320), whose output focal plain is equipped with three bundled fibers corresponding to three different wavelengths and the light is led to three photomultipliers, respectively. Another multi-channel analyzer (1024 address, MAX3000 system) was set up to measure several spectral lines on 100-nm wavelength region at an instance. Observation position in the plasma space is adjusted at the radial center of the torch and 10mm below from the end of the coil.

The time-varying plasma temperature for different gaseous composition (Ar, Ar-N2, Ar-CO2) at atmospheric pressures condition with a power of 30 kW is given in Fig. 6. The temperature was obtained from the Boltzmann plot of two spectral lines emitted from Ar neutral lines. The average temperature across the plasma diameter measured as the exciting temperature of Ar atom thus estimated shows that it changes periodically from 16,000 to 8,000 K corresponding to the pulsation of the plasma. It can be noticed that the minimum temperature appears in a cycle is controlled with changing the SCL level. Furthermore, the difference of cooling effect is apparent between the gaseous medium, Ar, N2 and CO2. These charac-

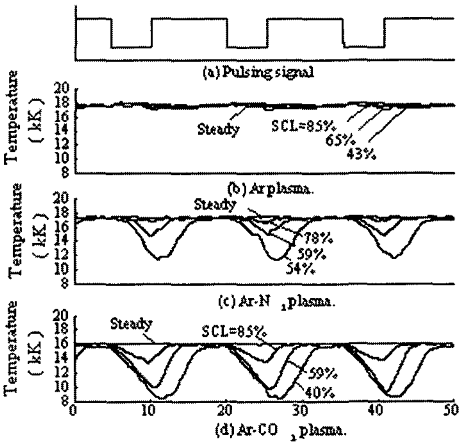

Fig. 6 Time Variation of Ar Excitation Temperature in Pulsed induction Plasma (760-torr, 30kW)

teristic is reflected by the dissociation reaction of molecular gases and partially by the electro-negative property of O atom. It should be noticed that such drastic change of the plasma temperature by the pulsation was not able to expect from the the oretical calculation based on the LTE modeling[1, 2]. Furthermore, the other recent experiments showed a large deviation from the theoretical result from time-dependent equilibrium model with respect to the electron and heavy particle temperature even under the atmospheric pressure level, if the induction plasma is pulsated[5].

Time-dependent radiation intensity of Ar, N, and H spectral lines were also measured in atmospheric Ar-H2 and Ar-N_2 pulsing plasmas operated at 17-kW power[6]. The spectral intensity of N and H atoms normalized against the intensity at steady state level was found to have an inherent rise and fall time constant, respectively, for example, N atom has extremely slow rise time, while H atom has a sharp rise and slow decay. This phenomena is not able to be explained again from the LTE modeling and implies an important situation that non-chemical equilibrium effects are occurring in the flux density of N or H radical species corresponding to the pulsing operation. This is supported with a recent theoretical work, where the reaction kinetics of all the chemical species are introduced into the r.f. induction plasma code[7]. The result shows that after the pulse off of the r.f. coil current, almost 1 to 2 ms is necessary for the plasma concentration to converge to a steady state equilibrium condition, for example, in atmospheric N_2 plasma.

4. 2 Development of New Quenching Gas for Power Circuit Breaker

The second application of the high pressure pulse modulated induction plasma lies in the high power circuit breaker industry. The main quenching gas used in this apparatus now is SF6, which has a strong electron affinity capability and shows an extremely high dielectric strength as well as an arc quenching performance. The COP3 conference in 1997 at Kyoto, however, specified this gas as one of global warming gases because of its higher GW value of 24,000 compared to that of CO2. The industry in this field thus should start to investigate new arc quenching gases necessary for high power circuit breaker, which should be friendly with earth circumstance alternative to SF6 gas. Although a number of researches and trials are necessary for the design, electrode and nozzle materials etc., the time-dependent characteristics of the pulsed induction plasmas including candidate gases (N2, O2, Air, CO2 etc.) is quite useful as a standard test facility to determine basically the inherent time constant for each gases, with respects to the plasma decaying phenomena,

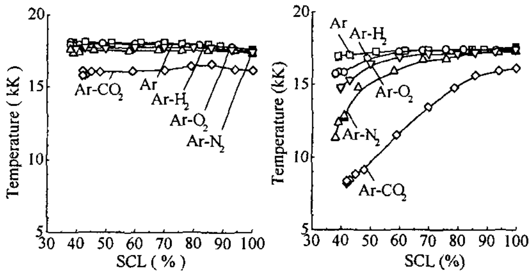

Fig. 7 Minimum and Maximum Temperature in a Pulse Modulation Cycle for 760-torr, 30-kW Induction Thermal Plasma

that is, interruption of high pressure arc plasma.

Fig. 7 shows the minimum and maximum plasma temperature appear in the pulse modulation cycle for 760-torr and 30-kW case. The maximum temperature, which appears after the pulse on action is hardly changed with the SCL level from 100 to 40 % and also with the sort of gases, with taking the value around 17,000 K. Remarkable change is, however, found in the minimum temperature appears just prior to the pulse on action. A general aspect recobnized in the figure is that lower the SCL level, lower the minimum temperature commonly for the molecular gases. Among the candidate gases, CO2 gas has a strong effect to decrease the plasma temperature during the pulse off period. The decaying of plasma temperature is almost proportional to the down of the SCL level and it reaches to around 6,000 K at SCL =40 %, where the electron density or the electrical conductivity is quite low. Although the reason for this should be studied further from the viewpoint of molecular dissociation, electron affinity property as well as EEDF (electron energy distribution function), the experiment shows clearly that the CO2 gas has relatively higher performance to quench the plasma temperature effectively, compared to the other N2, O2, H2 gases.

5. OTHER REMARKABLE FEATURES

Fig. 8 explains schematically the concept of pulsation in thermal plasmas which has been introduced firstly here. The pulsing technique has been relatively well understood and utilized in the low temperature, cold plasma region, mainly for increasing the energy and the number density of electron and radical species, with preventing from breakdown to thermal plasma region. On the other side, the thermal plasma is established only after such dielectric breakdown of gaseous medium through cold plasma region and it shows a quite steady feature even for further excess of energy input. The high pressure plasmas in inductively coupled or dc mode as well as the nuclear fusion plasma are typical examples of such steady and final mode of plasmas. Obviously, a transition phase exists between these two types of plasmas, which is called as the breakdown or extinguish phase. The introduction of pulsation in the thermal plasma done here gives a temporally returning back to the transition phase during pulse off period.

The main feature of the transition phase is that several non-equilibrium effects are existing, including a difference between electron and heavy particle temperature, radical specie density as well as chemical reaction rates, which are deviated considerably from the equilibrium state. This unique phase should be more utilized for the material processing, especially tne synthesis of new functional material with high efficiency and high rate. Thus, the meaning of the pulsation in the thermal plasma side is considered to give a quick quenching or cooling of the plasma in the time domain, aiming at returning to the transition phase where the several chemical species co-exist under non-equilibrium condition in both its energy and concentration.

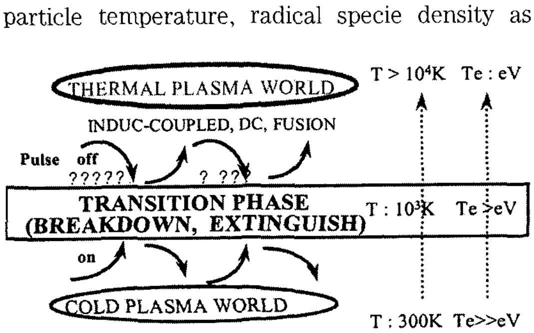

Fig. 8 Concept of Pulsation in Plasmas

Fig. 9 shows the component of power consumption in induction thermal plasma system for both standard vacuum tube and MOSFET transistor power supply[9]. The power dissipation was measured at each part by calorimetric method using water flow. As a common power consumption part for both system are the discharge tube and the work coil, which are around 13 % and 6 %, respectively. The most remarkable difference can be found in the power source part, that is, 59 % for

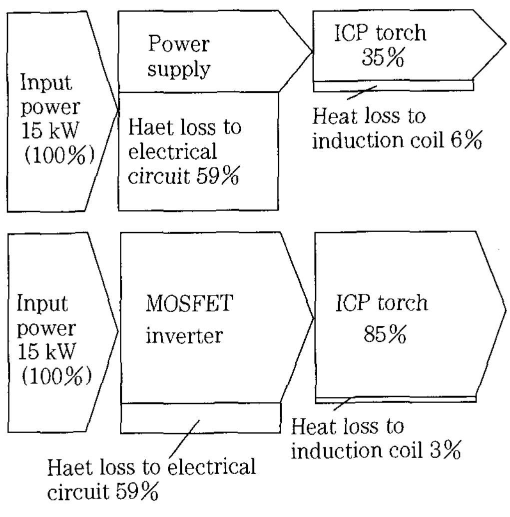

Fig. 9 Energy Balance in Induction Thermal Plasma Torch (After Sakakibara et.al ref.[9])

vacuum tube system and 5 % for MOSFET transistor system. The difference reflects directly to the input power to the plasma and especially high efficiency of around 85 % is achieved in the MOSFET system, while a quite low efficiency of 35 % is estimated in the conventional vacuum tube system. This is an example of the measurement of power dissipation for a certain systems exist. The actual situation is, however, not so far from the result obtained here.

6. SUMMARY

The inductively-coupled radio frequency plasma was successfully generated under a pulse modulated mode at a high pressure of 100 kPa and a power of 40 kW, by using semiconductor inverter power supply. Although the power electronics technique gives the standard feasibility to control the plasma power in time domain rather than the conventional amplitude domain, its characteristic feature gives other important possibilities to produce intentionally a non-equilibrium state of particle temperatures and the flux density of radical species or to control the thermal flux to the substrate in case of synthesis or spraying, both aiming at an advanced material processing. The dynamic characteristic of the pulsated plasma including diminish and re-ignition phase can also be adopted to the analysis of high pressure arc plasma quenching process found in power circuit breakers.

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