Fundamental study and applications of pulse-modulated induction thermal plasma

氏名	MD. MOFAZZAL HOSSAIN
生年月日	
本籍	バングラディシュ
学位の種類	博士（学術）
学位記番号	博甲第548号
学位授与の日付	2003年3月25日
学位授与の要件	課程博士（学位規則第4条第1項）
学位授与の題目	Fundamental Study and Applications of Pulse-Modulated Induction Thermal Plasma(パルス変調誘導熱プラズマの基礎研究と応用)
論文審査委員(主査)	高嶋 武（工学部・教授）
論文審査委員(副査)	久米田 稔（工学部・教授）
	山田 外史（自然計測応用研究センター・教授）
	岩原 正吉（工学部・教授）田中 康規（工学部・助教授）

学位論文要旨

ABSTRACT

A promising new method (pulse-modulation) for induction plasma discharge has been described. The pulse-modulated induction thermal plasma (PMITP) has been simulated to investigate the impacts of molecular gases injected into argon plasma and the extinguishing phenomena, to predict stable and unstable operating region, and to investigate the transient behavior of plasma. Simulation has been done using a two-dimensional local thermal equilibrium (LTE) code for the same operating conditions as those of experiment. The extinguishing phenomena and stable and unstable operating regions are predicted in terms of duty factor (DF, ratio of on-time to time period of pulsing signal) and shimmer current level (SCL, ratio of lower to higher current level). Both experimental and simulated results reveal that, inclusion of dissociative molecular gases greatly shrinks the stable discharge region due to molecular dissociation mainly. It was found that stable discharge region predicted numerically was smaller than that of experimental one. This implies that non-LTE plasma has a wider operating zone than that of LTE plasma. The time-dependent plasma temperature and hence the integrated radiation intensity for atomic argon spectral line (751 nm) that characterizes the plasma behavior, has been calculated. It is found that, transient plasma response remains almost independent of SCL during off-pulse, whereas, slows down at decreased SCL during on-pulse. Small disagreements are observed between experimental and simulated findings especially, at lower SCL, and for pure argon plasma due to the LTE assumption in simulation. On the contrary, pulse-modulated plasma strongly deviates from LTE at lower SCL, and with pure argon gas injection.

1. Introduction

Inductive thermal plasma, an electrodeless contamination free highly radiative plasma source, has been found widespread laboratory and industrial applications. Even though, some applications of induction plasma [1] are already well established, optimization and automation of discharge are the forefront of current research activities. Since 1961 after Reed [2], a significant advancement of inductive plasma technology has been achieved. A huge number of works, both experimental and theoretical has been published that concerned the steady state plasma discharge. A few researchers have paid attention to the transient plasma nature [3-6]. The limitations of conventional steady discharge are (i) the transient analysis is not possible, (ii) cannot perturb the thermal state of plasma instantaneously and (iii) cannot generate non-equilibrium effects at the plasma core.

The purposes of the present study are: (i) to investigate the influences of several molecular gases over the steady and transient behavior of PMITP, because molecular gases are advantageous in material processing; (ii) to investigate the extinguishing phenomena, and to determine the limiting values of DF and SCL, and hence to obtain stable and unstable operating regions in terms of DF and SCL; (iii) to elucidate the transient behavior of PMITP. The transient analysis is important for two reasons (i) in searching an alternative of high-grade greenhouse gas SF_6 used in circuit breaker, and (ii) transient behavior affects the materials treatment in heat transfer and quenching.

In the present work I have simulated the PMITP to investigate the above facts using a two-dimensional LTE code. A comprehensive discussion is made by comparing parts of the simulated results with the corresponding experimental results, and reasonable agreements have been found among them. The remaining discrepancies are explained with probable reasons.

2. Concept of Pulse-Amplitude-Modulation

To overcome the limitations of steady discharge, pulse-modulated induction thermal plasma concept is developed. In PMITP, the high frequency and high amplitude current is amplitude modulated prior to supply it to the load coil, surrounding the torch wall. The principle of pulse modulation is described in Fig.1. The controllable parameters related to PMITP are pulse T_{on}, T_{off}, duty factor (DF), and shimmer current level (SCL). DF and SCL can be defined as follows according to Fig.1.

$$SCL(\%) = \frac{\text{Amplitude of current during} T_{off} \text{ (a)}}{\text{Amplitude of current during } T_{on} \text{(b)}} \times 100$$

and

$$DF(\%) = \frac{T_{on}}{T_{on} + T_{off}} \times 100$$

where, T_{on} and T_{off} are on and off-times of pulsing signal respectively.

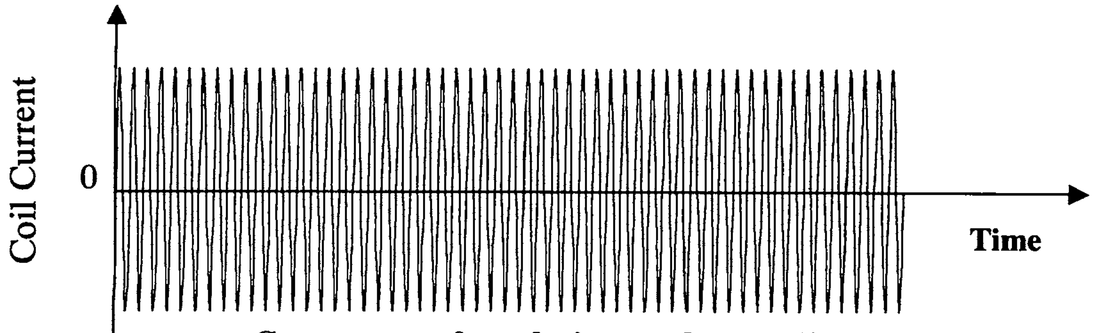
The most attractive and unique features of PMITP are:

(i) Changing the SCL, the effective plasma power can be changed keeping the maximum power level unchanged.

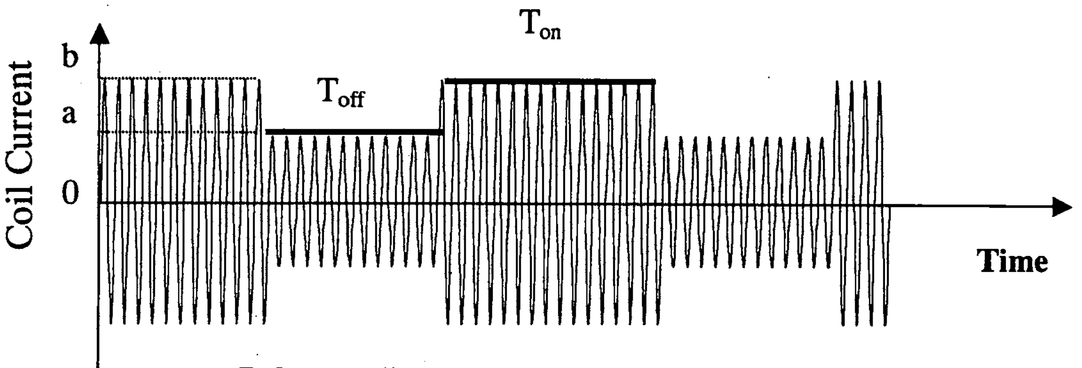
(ii) Input power to plasma can be controlled in time domain by controlling the duty factor.

(iii) Periodic changes of plasma particle density can be achieved in accord with the pulsing signal.

(iv) Successive application of very high and low electromagnetic fields and hence, the heat flux



Current wave form during steady state discharge



Pulse amplitude modulated current wave form

Fig.1 Pulse amplitude modulation of RF coil current for PMITP

introduces non-equilibrium effects, which might be very useful in materials processing.

(v) Periodic transition of coil current drives the plasma in local thermal equilibrium (LTE, where, T_e=T_h) and non-LTE (T_e>T_h) mode, at the end of on-pulse and off-pulse respectively.

3. Experimental Setup

The high frequency (0.45 MHz) power supply system consists of a rectifier (AC-DC converter), inverter (DC-AC converter), low frequency pulse generator for pulse amplitude modulation (PAM), and impedance matching network. The inverter consists of two MOSFET (Metal Oxide Semiconductor Field Effect Transistor, rated 150V/460A) produces the high frequency (0.45 MHz) AC power. A solid state power supply system (HF0030W45MS, Fuji Electric Co., Ltd.), which incorporates all of the above solid state devices and matching network except the load coil, was employed for a continuous electric power supply (maximum 50 kW).

Fig.2 describes the schematic geometry and dimensions of the induction plasma torch. The torch has a standard configuration of two co-axial tubes of 370 mm length and surrounded by water-cooled 8-turn RF-coil and serves to couple energy into the plasma. The inner diameter of the inner quartz tube and the outer diameter of the outer Pyrex tube are 70 and 95 mm respectively. In order to protect the torch from overheating, cooling water was passed through in the upward direction between the quartz and Pyrex tubes. The gas was injected into the torch through the sheath channel tangentially with a swirl to make the discharge stable and protect the torch wall from over heating.

The plasma emission was taken by an optical system (camera) and transmitted through an optical fiber. The optical signal was passed through a slit, into the monochromator. The emission intensity was monochromated by a (JOBIN YVON HR-320) for the selected wavelength, which came from an atomic spectral line of argon. The monochromated optical signal was then passed through the optical fiber into the photomultiplier (Hamamatsu, R928) with a response time of 70 ns. The photomultiplier converted the optical signal into an electrical signal as well as amplified that. This detected signal of the radiation intensity, the coil current, and the pulsing signal were digitized and stored simultaneously by a multi-channel digital oscilloscope (DL706E, Yokogawa Electric Co.) with a sampling rate of 2 MHz.

4. Simulation Details

4.1 Assumptions and Governing Equations

In this work, the plasma is assumed to be optically thin and in local thermodynamic equilibrium. The flow is assumed to be two-dimensional, steady, laminar, and axisymmetric with negligible viscous dissipation. Under these assumptions, the present model solves the time-dependent conservation equations along with the vector potential form of Maxwell's equations. The governing conservation equations and boundary conditions can be found in Ref. [7]

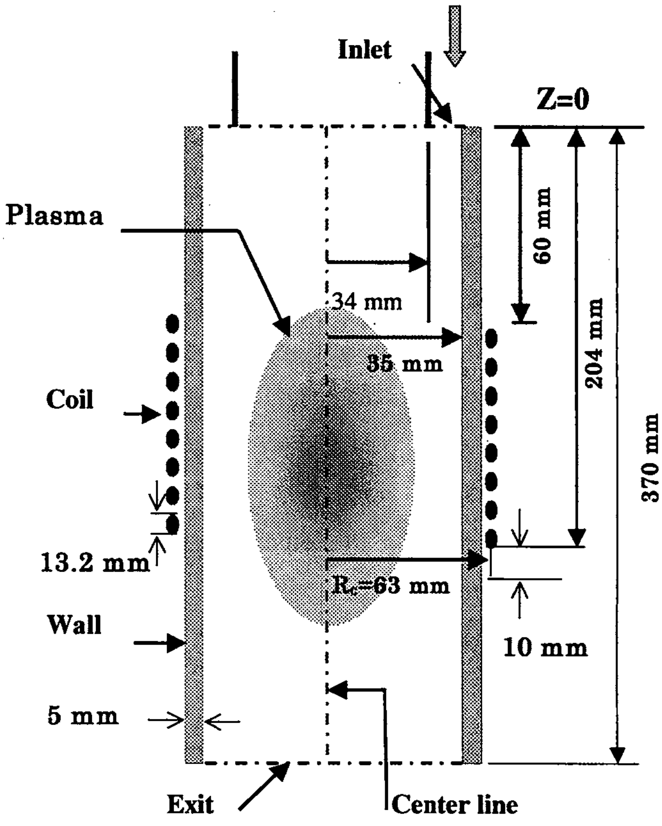


Fig.2 Schematic geometry of the PMITP torch

4.2 Calculation Procedure and Thermophysical Properties

Calculation is performed for a PMITP torch whose schematic with the definitions of the parameters is illustrated in Fig.2. Table-1 outlined the operating conditions. Time step of each iteration, is 10 μs throughout the calculation. The calculations are carried out for a non-uniform grid system having 36 radial and 92 axial nodes. Using the SIMPLER algorithm of Patankar [8], the conservation equations and vector potential form of Maxwell's equation are solved for both steady and pulse-modulated mode. The thermophysical properties of Ar, O_2, N_2, H_2, and CO_2 gases required for simulation include viscosity, specific heat at constant pressure, electrical and thermal conductivity, mass density, and radiative loss coefficient. The transport properties were calculated under thermal equilibrium conditions using Chapman-Enskog first approximation of Boltzmann Equation.

5. Results and Discussions

5.1 Extinguishing Phenomena and Operating Region

The diminishing/extinguishing nature of temporal induction plasma for instance, around the critical duty factor is investigated. For a duty factor beyond the critical limit (60.6%) the time varying mode of plasma sustained for a few cycles and then diminished. This phenomenon may have the following explanation: at the beginning of pulse modulation mode, plasma was sufficiently conductive to be discharged, however, temperature gradually decreased, and reached at a level from where eventually re-ignition was not possible, and the discharge seized. The stable and unstable operating regions, determined through experiment, are compared here with the simulated ones as displayed in Fig.3. It should be noted here that the operating regions are found wider in experiment than those of simulation for all gas combinations. Because, experimental plasma is a non-LTE plasma where $T_e > T_h$ and a non-LTE plasma can sustain even at lower power level. In such circumstances, the electrons, accelerated in the induced electromagnetic field, and heat the non-equilibrium thermal plasma, even at lower power level. In case of practical discharge, the molecular dissociation plays the key role in sustaining the non-equilibrium thermal plasma. However, dissociative attachment and charge transfer collisions play a vital role in the discharge. The discrepancies are found severe in case of pure argon especially at

Table -1: Operating conditions for experiment and simulation

Power:	30/27 kW	Shimmer Current Level:	40-90%
Pressure:	0.1 MPa	Flow-rate of Argon:	100 l/min
Frequency:	0.45 MHz	Secondary Gas Flow-rate of $H_2/N_2/CO_2$:	2.5 l/min
Pulse on-time:	10 ms		
Duty Factor:	0.8-76.9%		

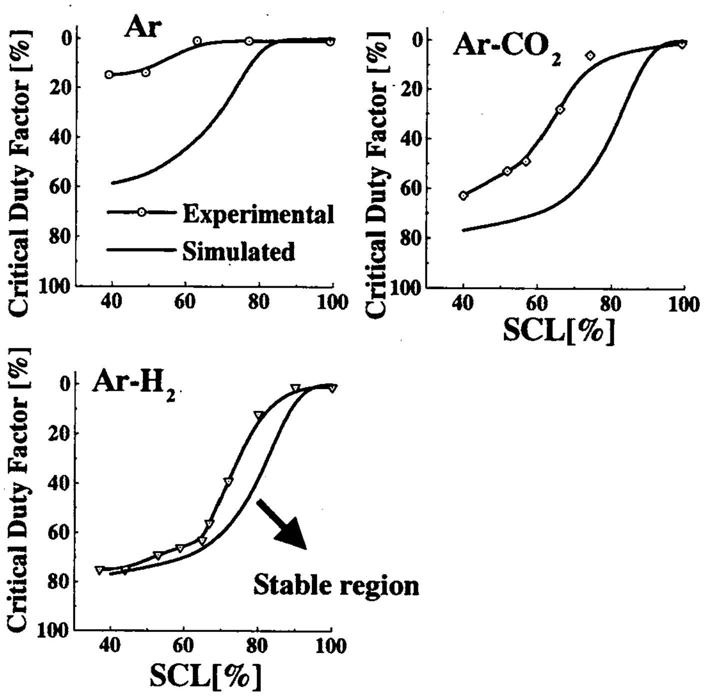


Fig.3 Comparison between experimental and simulated stable operating region.

lower SCL because monatomic gas PMITP strongly deviates from LTE.

5.2 Transient Behavior of PMITP

The simulated temporal radiation intensity of ArI (751 nm) are compared with those of experiment for Ar and 2.4% CO_2 admixed Ar plasmas that describes the instants over the modulation cycle where the maximum deviation takes place (Fig.4). These figures show that, the experimental plasma response is much faster than that of simulated ones during the on-pulsing transition and have similar response during off-pulse transition. The reason is that, experimental PMITP is likely to be a non-equilibrium plasma at the end of off-pulse where electron temperature may be much higher than that of heavy particles; and a non-equilibrium plasma has a faster response in a sudden applied electromagnetic field. Whereas, at the end of off-pulse simulated PMITP is in LTE. At the end of on-pulse experimental PMITP reaches to LTE and both plasmas have similar state. Thus, the response during off-pulse is similar in both cases. The plasma response has been predicted quantitatively calculating the response times. It is found that plasma response is slower at lower SCL and gradually becomes faster with the increase of SCL during on-pulse transition. This is because, at lower SCL more drop of temperature occurs during off-pulse so that an additional time is required to raise the temperature at a level

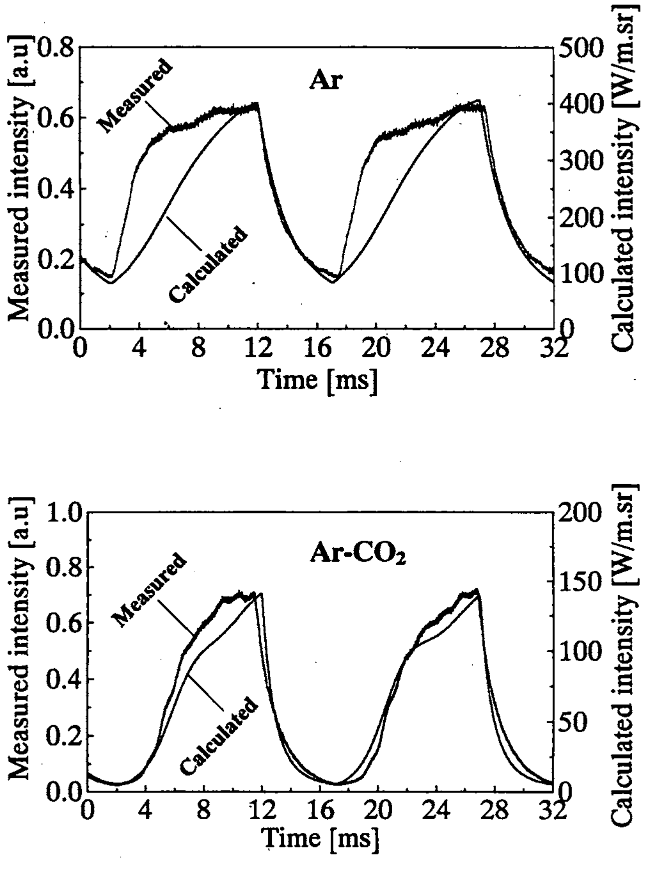


Fig.4 Comparison between the measured and calculated radiation intensity of ArI (751 nm). The operating conditions are: power 30/27 kW, SCL 60%, DF 67%, pressure 0.1 MPa, flow-rate 100 slpm Ar and 2.5 slpm CO_2. Axial position: 10 mm down to the end-coil.

equivalent to higher SCL. Response is almost independent of SCL during off-pulse transition, because at the beginning of off-pulse plasma stays at the same condition for all SCL. And the maximum deviation between experimental and simulated response times are observed at lower SCL, because at lower SCL experimental pulse modulated plasma strongly deviates from LTE due to the insufficient power input and continuous cold gas injection.

6. Calculation in Two-Temperature State

From the above discussion it is evident that PMITP stays out of LTE at the end of off-pulse, especially at lower SCL. Thus, it is necessary for the accurate analysis of PMITP to calculate in two-temperature state. With that purpose, I have calculated the number density in reaction kinetic approach considering chemical equilibrium, and hence, the thermophysical properties of argon plasma at atmospheric pressure as a starting point of future work.

7. Concluding Remarks and Recommendation for Future Work

Throughout this work, the transient characteristics of argon and molecular gas seeded argon plasmas are studied elaborately through experimental and numerical efforts in pulse amplitude modulation approach. The spatial plasma temperature distributions within the torch space have been studied at steady state and pulse-modulated operating condition. Rigorous comparison was made between experimental and numerically simulated results that help to clear the discharge phenomena, LTE and non-LTE phenomena, and to discern the limitations of LTE modeling. The findings of the present study can be summarized in the following points:

- PMITP, a new approach may find potential applications in material processing due to its non-equilibrium effects during the pulsing transition.
- Molecular gases greatly shrink the operating region due to dissociation mainly.
- Non-LTE plasma (experimental PMITP) has a wider operating region than that of LTE plasma, which implies that non-LTE plasma can be sustained even at lower power level.
- It is evident from the analysis that CO_2 has the strongest extinguishing nature than that of Ar, N_2, O_2 and H_2.
- Transient plasma response drastically slowed down at lower SCL during the on-pulse, whereas, SCL hardly affects the response during the off-pulse transition.
- Molecular dissociation, recombination, and ionization process deadly affects the transient plasma characteristics. LTE model cannot simulate PMITP accurately at lower SCL and pressure; however, LTE model can simulate PMITP at higher SCL and pressure satisfactorily.

Thus, the above facts lead to develop a two-temperature model considering chemical reactions for the precise analysis of PMITP

References

[1] M. I. Boulos, P. Fauchais, and E. Pfender, *Thermal Plasmas-Fundamentals and Applications*, vol. 1, Plenum, New York, (1994).

[2] T. B. Reed, *J. Appl. Phys.* vol. 32, pp. 821-824 (1961).

[3] P. Meubus, *Can. J. Phys.*, vol. 60, pp. 886-892 (1982).

[4] J. M. de Regt, Van der Mullen, and D. C. Schram, *Phys. Rev*, vol. 52, pp. 2982-2987 (1995).

[5] T. Ishigaki, X. Fan, T. Sakuta, T. Banjo and Y. Shibuya, *Appl. Phys. Lett.* Vol. 71, pp. 3787-3789 (1997)

[6] T. Sakuta, K. C. Paul, M. Katsuki and T. Ishigaki, *J. Appl.Phys.*, vol. 85, pp. 1372-1377 (1999).

[7] M. M. Hossain, Y. Hashimoto, Y. Tanaka, K. C. Paul, and T. Sakuta, *IEEE Trans. on Plasma Science,* vol. 30, pp. 327-337 (2002).

[8] S. V. Patankar, *Numerical Fluid Flow and Heat Transfer,* Hemisphere, New York (1980).

学位論文審査結果の要旨

各審査委員による学位論文の検討の後，平成15年1月21日第1回論文審査委員会を開催し，平成15年1月27日に口頭発表を行った。この結果を踏まえ同日第2回論文審査委員会を開催し，以下のように判定した。

パルス変調誘導熱プラズマPMITPは，従来までの定常型誘導熱プラズマと異なり，コイル電流を振幅変調することにより熱プラズマを時間的に変動させ，熱プラズマ温度・流速を制御する新方式である。申請者は，PMITP方式の確立をめざし，局所熱平衡を仮定した時間依存形の二次元電磁熱流体解析プログラムを開発し，その安定維持範囲，過渡応答特性，付加ガスH_2，N_2，O_2およびCO_2の影響を調べるとともに実験結果とも比較し，以下の事項を明らかにした。(1) PMITPは，電流変調率SCLおよびDuty比が小さいほど安定維持が困難になり，特にCO_2を導入すると安定維持範囲が小さくなる。(2) PMITPの過渡応答特性も分子ガスを導入すると遅くなる。(3) 過渡特性時間のうち，オン遅延時間のみがSCL依存性を持っている。(4) 安定維持範囲およびオン遅延時間についてCO_2を混合させた場合に実験結果と本モデルでの計算結果とがほぼ合致する。しかしArで低SCLの場合，実験結果との間に大きな差が見出される。これはオフからオン動作への遷移過程でPMITPが熱的非平衡状態になっているためである。

以上の研究成果は，熱プラズマの新しい制御手法PMITP方式の確立に対する多くの知見を得ており，高く評価できる。従って，本論文は博士論文に値するものと判定する。