

行政院國家科學委員會補助專題研究計畫簡易報告

常壓射頻電容耦合式電漿束之研究(三年)

Development and Characterization of an Atmospheric-pressure
Capacitively Coupled Plasma Jet (3 Year)

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行政院國家科學委員會專題研究計畫期中報告

常壓射頻電容耦合式電漿束之研究(第一年)

Development and Characterization of an Atmospheric-pressure Capacitively Coupled Plasma Jet (First Year)

計畫編號：NSC-96-2628-E-009-134-MY3

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主持人：吳宗信 國立交通大學機械工程學系

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中文摘要

在過去十年中，大氣電漿逐漸替代低壓電漿作為材料表面處理的應用。其重要性是由於它相對低廉的設備費用，及更容易的操作條件和在更高的靈活性在工業上的應用。其中已經發展的大氣電漿源之中，又以非熱平衡『常壓射頻電容耦合式電漿束』（簡稱常壓電漿束）引起了最多的注意。主要乃因為其應用範圍相當廣闊，包括半導體製程光阻去除，清潔，消毒，表面改質和薄膜沈積等等，相當廣泛。

第一年，在實驗部分，我們將設計，建立和驗證基本常壓電漿束設備。基本先已氬氣及氬氣或是兩者混合氣體做為量測實驗參數定義（電壓-電流、電流-功率參數關係）。我們將在常壓電漿束出口位置使用幾種量測方式定義電漿特性。這幾種量測方式包括使用粒子影像測速儀(PIV)量測速度；使用熱電偶線量測溫度分佈。另外在電漿系統數值模擬部份中我們以全域式流體數值模組技術估計為電漿密度及電子溫度。在數值部分，我們已修改現有之平行化流體數值模組有線差分法架構從 2D 改為軸對稱，並利用進行氬氣常壓電漿束之模擬。在報告最後，將對未來計劃工作進行簡單描述。

關鍵字：常壓電漿束，氬氣，氬氣，流體數值模組。

Abstract

In this proposed three-year project, we intend to develop and systematically characterize a non-thermal atmospheric-pressure capacitively coupled plasma jet (APPJ), which is able to generate reactive atoms or radicals of practical interest. Interested radicals may include oxygen- (electronegative) and nitrogen-based (electropositive) species, which have tremendous practical applications. Research approaches include both experiments and modelings.

In the first year, in the experimental part we have designed, constructed and verified a testing rig for the basic APPJ experiment. Operating window (e.g., I-V and I-P characteristics) for the basic configuration using helium, argon gas or mixture of both have been identified. We have made several measurements in the post-glow region to characterize the plasma. These measurements include velocity field using a particle image velocimeter (PIV), temperature distribution using a thermocouple. In the modeling part we have developed a parallelized 2-D and 2-D axisymmetric plasma fluid modeling code, which was used to predict the plasma properties between concentric electrodes under atmospheric-pressure condition. Future works are outlined at the end of this report.

Keywords: atmospheric-pressure plasma jet, helium, argon, fluid modeling.

I. INTRODUCTION

It is well accepted that atmospheric-pressure plasmas do not have several inherited disadvantages as low-pressure plasmas do [Schutze *et al.*, 1998; Becker *et al.*, 2004; Moravej and Hicks, 2006]. Thus, there exists a great interest in atmospheric-pressure plasmas, as can be seen from several international conferences in the past five years [2000-2005]. Types of atmospheric-pressure plasmas [Schutze *et al.*, 1998 and references cited therein] include transferred arc and plasma torch, corona discharge, dielectric barrier discharge, and atmospheric-pressure plasma jet.

Plasma torch is one kind of thermal equilibrium plasmas, in which the temperature (10,000-20,000 K) of electrons, ions and neutrals are approximately the same, while the other three kinds are all non-thermal ("cold") non-equilibrium plasmas, in which the electron temperature (10^4 - 10^5 K) is much higher than those of ions and neutrals (~300K). The former is limited in applications due to its high temperature,

while the latter are more widely used due to its low temperature.

In corona discharges, plasmas are generated around the tip a needle within ~ 0.5 mm, where the electric field is very large and highly non-uniform. The corona discharge can be considered as a Townsend discharge or a negative glow discharge depending upon the field and potential distribution. Micro-discharges and streamers are generated in the plasma. Operating voltage is in the range of 10-50 kV.

In dielectric barrier discharge, which is often called “silent discharge”, it consists of two electrodes with at least one is coated with dielectrics. The discharge is maintained through a series of micro-discharges, lasting for 10-100 ns, and randomly distributed in space and time, which are often called “streamers”. Operating voltage in the range of 5-25 kV. Two major drawbacks are shared for the corona discharge and the dielectric barrier discharge. One is the high breakdown voltage and the other is the difficulty of maintaining a uniform glow like low-pressure plasma.

In atmospheric-pressure plasma jet, it often consists of two coaxial electrodes through which a mixture of gases flow. By applying 13.56 MHz RF power to the central electrode at a voltage in the range of several hundred volts, the gas discharge can be ignited and maintained over a fairly large range of conditions. Normally the atmospheric-pressure plasma jet is operated in the “abnormal glow” regime, in which the voltage increases with increasing current, while the low-pressure plasma is often operated in the “normal glow” regime, in which the voltage remains constant with increasing current [Schutze *et al.*, 1998].

In this report, we describe the progress of the project in the first year, which aims at simulating the atmospheric-pressure capacitively coupled plasma jet without considering neutral flow field and setting up related experimental facilities and instrumentation for preliminary measurements.

II. EXPERIMENTAL METHOD

Figure 1 illustrates the sketch of a co-axial APPJ, which is powered by a RF source (13.56 MHz) with a matching box between the RF power and APPJ to reduce the power reflection from the APPJ. The APPJ consists of two 180 mm long concentric electrodes made of metal that may be copper, stainless steel or aluminum. The inner diameter of the outer grounded electrode is 14.4 mm with water cooling, while the inner electrode is directly connected to the RF power source. Gap spacing between two electrodes is 1.2 mm and is adjustable if necessary. Either helium or argon is passed through the annular space between the electrodes.

Basic discharge parameters, such as the input RF power, RF voltage, RF current and phase angle, are measured by an RF impedance analyzer (MKS VI-probe-4100). The voltage and current wave form of the discharge were investigated by a current probe

(Tektronix TCP312) and a high-voltage probe (Tektronix P6015A) through a digital oscilloscope (Tektronix TDS1012B). Planar flow velocities near the APPJ are measured using a particle-image-velocimeter (PIV) (15 fps, TSI Inc.) with a double-pulsed Nd:Yag laser (30 mJ) as the light source of optical sheet. Note seeding particles (SiO_2) with nominal size of $20 \mu\text{m}$ are used for PIV measurements. Plasma is extinguished should the smaller size of particles were chosen since the charged species of plasma (electrons, ions) are much easier to attach onto the surface of the seeding particles. Typical test conditions include RF power in the range of 80-150 W and calculated average velocity between the annular space in the range of 3.2-15 m/s, which corresponds to the Reynolds numbers (based on the gap distance) in the range of 500-2,500. The temperature of effluent discharge gas is measured with a T-type thermocouple, which was mounted on a manually controlled stage.

III. NUMERICAL METHOD

Fluid Modeling Equations

As mentioned in previous section, electron and ion density are calculated as a function of time and space resulting from the solution of species continuity equation, species momentum equation, species energy equation, and field equations. Since the fluid modeling equations are quite similar for most of the gas discharges, we only summarize a typical set of equations in the following as the model equations for the purpose of demonstration. We could then possibly infer the numerical performance for other sets of model equations from the results of the present study. Note we neglect convection effects in the present study.

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \vec{\Gamma}_p = \sum_{i=1}^{r_p} S_{p_i} \quad p=1, \dots, k \quad (1)$$

where n_p is the number density of ion species p , k is the number of ion species, r_p is the number of reaction channels that involve the creation and destroy of ion species p , and $\vec{\Gamma}_p$ is the particle flux as, based on drift-diffusion approximation,

$$\vec{\Gamma}_p = \text{sign}(q_p) \mu_p n_p \vec{E} - D_p \nabla n_p \quad (1a)$$

$$\vec{E} = -\nabla \phi \quad (1b)$$

where $\vec{E}$, μ_p , D_p and α_{iz} is the electric field, electron mobility, electron diffusivity, and ionization rate, respectively. Note the form of source term S_{p_i} can be modified or added according to the modeled reactions describing how the ion species p is generated or destroyed in reaction channel i . Boundary conditions at walls are applied considering thermal diffusion, drift and diffusion fluxes.

Continuity equation for electron species e can be written as,

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{\Gamma}_e = \sum_{i=1}^{r_e} S_{e_i} \quad (2)$$

where n_e is the number density of ions, r_e is the number of reaction channels that involve the creation and destroy of electron, and $\vec{\Gamma}_e$ is the corresponding particle flux as, based on drift-diffusion approximation,

$$\vec{\Gamma}_e = -\mu_e n_e \vec{E} - D_e \vec{\nabla} n_e \quad (2a)$$

where μ_e and D_e is the electron mobility and electron diffusivity, respectively. Similar to S_{P_i} , the form of S_{e_i} can also be modified or added according to the modeled reactions which generate or destroy the ion in reaction channel i . Boundary conditions at walls are applied considering thermal diffusion, drift and diffusion fluxes. Secondary electron emission can be readily added if necessary.

Continuity equation for **neutral species** can be written as,

$$\frac{\partial n_{uc}}{\partial t} + \vec{\nabla} \cdot \vec{\Gamma}_{uc} = \sum_{i=1}^{S_{uc}} S_{uc_i} \quad (3)$$

where n_{uc} is the number density of uncharged species uc , and $\vec{\Gamma}_{uc}$ is the corresponding particle flux, neglecting convection effects,

$$\vec{\Gamma}_{uc} = -D_{uc} \vec{\nabla} n_{uc} \quad (3a)$$

where D_{uc} is the diffusivity of uncharged species, which may be assumed to be zero if excited species is considered. Similarly, the form of S_{uc_i} can also be modified or added according to the modeled reactions which generate or destroy the species in reaction channel i . Neumann boundary conditions at walls are applied since no surface reactions are considered in the present study.

Electron energy density equation can be written as,

$$\frac{\partial n_e}{\partial t} + \vec{\nabla} \cdot \vec{\Gamma}_{n_e} = -e \vec{\Gamma}_e \cdot \vec{E} - \sum_{i=1}^S \mathcal{E}_i S_i + 3 \frac{m_e}{M} n_e k_B \nu_m (T_e - T_g) \quad (4)$$

where $n_e \left(= \frac{3}{2} n_e k_B T_e \right)$ is the electron energy density,

$\mathcal{E}_i$ is the energy loss for the i^{th} inelastic electron collision, k_B is the Boltzmann constant, ν_m is the momentum exchange collision frequency between electron (mass m_e) and background neutral (mass M), T_g is the background gas temperature that is assumed uniform here, and $\vec{\Gamma}_{n_e}$ is the corresponding electron energy density flux as

$$\vec{\Gamma}_{n_e} = \frac{5}{2} k_B T_e \vec{\Gamma}_e - \frac{5}{2} \frac{n_e k_B T_e}{m_e \nu_m} \vec{\nabla} (k_B T_e) \quad (4a)$$

Boundary conditions at walls are applied considering thermal diffusion, drift and diffusion

fluxes. Secondary electron emission can be readily added if necessary.

Poisson's equation can be written as

$$\nabla^2 \phi = -\frac{1}{\epsilon_0} \sum_{i=1}^{k+1} q_i n_i \quad (5)$$

Finite-difference Discretization

In this present study, we discretize the fluid modeling equations (1)-(5) through the use of finite-difference method. Since continuity equations (1)-(3) are similar, we only present the discretization for the equation (1). By employing backward Euler scheme for time integration and the Scharfetter-Gummel scheme for representing the particle flux and after tedious algebraic rearrangement, resulting typical discretized equation can be written as,

$$A_{m,n} n_{e,m+1,n}^{k+1} + B_{m,n} n_{e,m-1,n}^{k+1} + C_{m,n} n_{e,m,n+1}^{k+1} + D_{m,n} n_{e,m,n-1}^{k+1} + E_{m,n} n_{e,m,n}^{k+1} = \Delta t S_{e,m,n}^k + n_{e,m,n}^k \quad (6)$$

where

$$A_{m,n} = -\frac{\Delta t}{\Delta x^2} D_{e,m+1/2,n} \tilde{z}_{m+1/2,n} \frac{1}{e^{\tilde{z}_{m+1/2,n}} - 1} \quad (6a)$$

$$B_{m,n} = -\frac{\Delta t}{\Delta x^2} D_{e,m-1/2,n} \tilde{z}_{m-1/2,n} \frac{e^{\tilde{z}_{m-1/2,n}}}{e^{\tilde{z}_{m-1/2,n}} - 1} \quad (6b)$$

$$C_{m,n} = -\frac{\Delta t}{\Delta y^2} D_{e,m,n+1/2} \tilde{z}_{m,n+1/2} \frac{1}{e^{\tilde{z}_{m,n+1/2}} - 1} \quad (6c)$$

$$D_{m,n} = -\frac{\Delta t}{\Delta y^2} D_{e,m,n-1/2} \tilde{z}_{m,n-1/2} \frac{e^{\tilde{z}_{m,n-1/2}}}{e^{\tilde{z}_{m,n-1/2}} - 1} \quad (6d)$$

$$E_{m,n} = 1 + \frac{\Delta t}{\Delta x^2} \left(D_{e,m+1/2,n} \tilde{z}_{m+1/2,n} \frac{e^{\tilde{z}_{m+1/2,n}}}{e^{\tilde{z}_{m+1/2,n}} - 1} + D_{e,m-1/2,n} \tilde{z}_{m-1/2,n} \frac{1}{e^{\tilde{z}_{m-1/2,n}} - 1} \right) + \frac{\Delta t}{\Delta y^2} \left(D_{e,m,n+1/2} \tilde{z}_{m,n+1/2} \frac{e^{\tilde{z}_{m,n+1/2}}}{e^{\tilde{z}_{m,n+1/2}} - 1} + D_{e,m,n-1/2} \tilde{z}_{m,n-1/2} \frac{1}{e^{\tilde{z}_{m,n-1/2}} - 1} \right) \quad (6e)$$

$$\tilde{z}_{m+1/2,n} = \frac{(sign) \mu_{e,m+1/2,n} E_{m+1/2,n} \Delta x}{D_{e,m+1/2,n}} \quad (6f)$$

$$\tilde{z}_{m-1/2,n} = \frac{(sign) \mu_{e,m-1/2,n} E_{m-1/2,n} \Delta x}{D_{e,m-1/2,n}} \quad (6g)$$

$$\tilde{z}_{m,n+1/2} = \frac{(sign) \mu_{e,m,n+1/2} E_{m,n+1/2,n} \Delta x}{D_{e,m,n+1/2,n}} \quad (6h)$$

$$\tilde{z}_{m,n-1/2} = \frac{(sign) \mu_{e,m,n-1/2} E_{m,n-1/2,n} \Delta x}{D_{e,m,n-1/2,n}} \quad (6i)$$

Parallel Newton-Krylov-Swartz scheme

In this proposed study, we will apply the parallel Newton-Krylov-Swartz (NKS) scheme [Cai *et al.*, 1997] to solve the coupled nonlinear discretized equations, eqns. (6), as derived in previous section. All the functionals for each dependent variables form a global functional vector. Jacobian matrix is then computed based this global vector. Nevertheless, this treatment results in a fully implicit scheme, which allows much larger time step as compared to the semi-implicit or explicit scheme. Another advantage of solving the coupled equations directly, rather than solving the equations one by one or some heuristic way of coupling, is that it can have better time accuracy with appreciable time-step size, and much better parallel performance since the grain size is much larger. In this method, an inexact Newton iterative scheme is used to solve the coupled nonlinear discretized equations at each time step. The resulting Jacobian systems for the Newton

corrections are solved with a Krylov type method, relying directly only on iterative operations. All the entries of Jacobian will be computed using finite-difference method. The Krylov scheme requires preconditioning for achieving acceptable convergence speed of inner interactions. A good preconditioner saves time and memory by allowing fewer iterations in the Krylov loop and smaller storage for the Krylov space.

In this study, we utilized a parallel geometrically additive Schwarz preconditioner (GASPC) [Hwang and Cai, 2005] with an approximate solve in each subdomain. One- or multi-level overlapping GASPC can be easily achieved. This approximate solve in each subdomain can be either LU or ILU decomposition type. It was shown that this ASPC can greatly reduce the runtime required for inner iterations in an inexact Newton method [Hwang and Cai, 2005]. This results from that the smaller subdomain blocks maintain better cache residency and shorter convergence time for an approximate solve. In addition, either scheme will be used to solve the preconditioned matrix equation at each time step. By combining the ASPC with a Krylov (BiCG-STAB [H.A. Van Der Vorst, 1992] or GMRES [Saad and Schultz, 1986] in the present study within an inexact Newton method leads to a coherent parallelized solver: Netwon-Krylov-Schwarz (NKS) scheme [Cai *et al.*, 1997].

IV. RESULTS AND DISCUSSIONS

Preliminary results of the experiments and simulations are briefly summary as follows.

Experiments

Effect of gas flow rate on discharge characteristics

Fig. 2a and Fig. 2b shows the voltage as a function of current at various flow rates for argon and helium feed gas, respectively. It is clearly that the electrical characteristics is essentially the same at various flow rates for helium, while it does show some effect of flow rates for argon. Nevertheless, the effect is relatively small. In addition, the breakdown voltage of helium is generally larger than that of argon at the same current as expected.

Effects of electrode material on discharge characteristics

Fig. 3 shows the voltage as a function of current for an argon discharge with 30 slm at various inner electrode materials. The results show that the influence on electrical characteristics by using different metal materials for inner electrode is the very small. However, difference can still be seen at higher value of current. For the results presented later, the inner electrode is made of copper, unless otherwise specified.

He+ $\%O_2$ discharge characteristics

Fig. 4 show that I-V curves of helium discharge by mixing with different quantities of oxygen at 10 slm of helium. It is clearly that the addition of oxygen has greatly alters the electrical characteristics of helium discharge. The breakdown voltage for glow

discharge is 120, 210, 340 and 370 Volts, respectively, for pure helium, oxygen addition of 0.99%, 2.91% and 4.76%, which is attributed to easy electron attachment onto oxygen. With pure helium and with addition of oxygen up to 0.99%, the plasma shows typical characteristics of abnormal discharge (positive slope), in which voltage increases with increasing current. As 2.91% of the oxygen is added, the abnormal discharge occurs initially in a very narrow range of voltage and current, then the voltage decreases with increasing current (negative slope), and finally a typical normal-discharge region is observed, where the voltage levels off with increasing current (zero slope). As more oxygen (4.76%) is added, the abnormal-discharge range is even smaller and then the negative-slope region persists till the arc occurs. Explanations of these interesting phenomena requires further investigation in the future.

Figs. 5a-5d show the effect of absorbed power on the measured impedance, phase angle, resistance and reactance, respectively, at various additions of oxygen into 10 slm of helium. Impedance generally decreases with increasing absorbed power, while the current-leading phase angle decreases accordingly which becomes more resistive. Also the operating range of power increases with increasing addition of oxygen (from 250W to more than 700W). In addition, impedance increases with increasing amount of oxygen, but becomes almost the same as the oxygen is 2.91% or above. Note that impedance also increases with oxygen flow rate. For the same data, Fig. 5c shows that there exist a maximum resistance at some specific power that increases with increasing amount of oxygen addition. As breakdown occurs, resistance first increases with increasing power, reach a maximum value and then decrease further on. In addition, the reactance generally increases with increasing power as shown in Fig. 5d.

Gas temperature distribution in the APPJ

Fig. 6 and Fig. 7 shows two-dimensional temperature distribution of the discharged gas with 10 and 20 slm of pure argon, respectively, at power of 120 and 150W. The peak value of temperature is observed in the vicinity of the gap at the APPJ exit ($Z = 6 \sim 7.2$ mm, $y = -3 \sim -10$ mm). It decreases to about 323 K gradually at the $z = -60$ mm.

Velocity distribution

Fig. 8 shows the 2-D velocity distribution of the APPJ flow under the condition of Argon with 15 and 20 slm without gas discharge. The circulation region behind the central power electrode extended to downstream, when the gas flow rate increases. Fig. 9 shows the 2-D velocity distribution of the argon gas flow with gas discharge under the condition of argon with variable powers and flow rates.

Simulations

At this stage, simulation results still cannot compare with experimental results since the code is still under development. Thus, only preliminary results of simulation are presented here. Simulation

conditions include: 201x3 non-uniform grid points (quasi-1D), 1,000 RF cycles, 100 time step per RF cycle, and a sinusoidal voltage with $V_{pp}=400$ V. Assuming uniform background argon (500K), four species, including argon ion, electron, meta-stable argon and resonant argon, are included in the modeling. A simplified reaction mechanism considering nine reactions is summarized in Table 1 and was used in the present simulation. The ion mobility is obtained as a function of reduced electric field, while the electron mobility is pre-tabulated as a function of electron temperature through cross section data. The code was run with parallel computing using 2 processor with BCGS as the KSP linear equation solver, ASM as the preconditioner, and LU as the sub-domain solve.

Fig. 10 shows the plasma properties at various phases of a RF cycle. Results in Fig. 10a show that the electric field near the inner power electrode is larger than that near the outer ground electrode because of the smaller area of the inner electrode. But the difference is barely observed since the difference of areas is not large. Fig. 10b show the plasma density distributions of electron and ions. Note the ions are almost immobile due to much larger mass and fast oscillating field. The distribution is very similar to those found in low-pressure RF discharge, in which the bulk is almost quasi-neutral while the sheath is positively charged. Fig. 10c shows the distribution of electron temperature. In the bulk, the electron temperature is about 1.3-1.5 eV, which is in general lower than those found in low-pressure RF discharge due to frequent collision of electron with abundant neutral background argon. In addition, much higher electron temperatures are found near the sheath regions since much large electric fields exist in these regions, which can greatly accelerate the electrons to higher energies.

Fig. 11 shows the distribution of cycle-averaged plasma properties. The plasma potential is found to be 94 V. Asymmetric sheath is formed with inner sheath thickness ~ 0.3 mm and outer sheath thickness ~ 0.4 mm with the reason described earlier. The electron temperature is ~ 1.5 eV in the bulk while there exists two peaks near the sheath with value of 2.5 eV. Also the distribution of plasma density is not symmetric as expected.

Fig. 12 shows the cycle-averaged distribution of argon related species. Results show that the concentration of meta-stable argon is much higher (2.5 times) than that of argon ions, due to the much lower threshold energy of forming meta-stable argon as compared to ionization. Both the excited argons, especially the meta-stable argon, are more abundant near the inner electrode than near the outer electrode. This is due to the large electron energy in this region, which can excite ground-state argons more efficiently. In addition, the concentration of resonant argon is about 70% of the argon ion.

V. CONCLUSIONS AND FUTURE WORKS

In the current report, we have described the progress of our project in experiments and simulation of APPJ using helium and argon gases. Important conclusions are summarized as follows:

1. A test rig has been set up and verified for operation of APPJ using RF power.
2. Preliminary measurements of electrical properties, velocity fields, and temperature distribution have been made. Several interesting electrical properties have been found for oxygen addition into helium, which requires further investigation to understand the underlying physics.
3. A parallelized 2D fluid modeling code using finite-difference method has been developed and tested.
4. A preliminary simulation using concentric APPJ with RF power is conducted. Results are reasonably explained.

Future work includes detailed measurements of plasma properties within the APPJ at various operating conditions. In addition, the development of the N-S equation solver using cell-centered finite-volume method is currently in progress and will be combined with the present fluid modeling code to fully simulate the APPJ, which the project aims.

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Table 1. Reaction channels for the simulations of RF argon plasma APPJ.

No	Reaction	Energy	Rate constant
1	$e + \text{Ar} \rightarrow e + \text{Ar}$	0	Based on cross section
2	$e + \text{Ar} \rightarrow 2e + \text{Ar}^+$	15.9	Based on cross section
3	$e + \text{Ar} \rightarrow e + \text{Ar}m^*$	11.55	Based on cross section
4	$e + \text{Ar} \rightarrow e + \text{Ar}r^*$	11.62	Based on cross section
5	$e + \text{Ar}m^* \rightarrow 2e + \text{Ar}^+$	4.35	Based on cross section
6	$e + \text{Ar}m^* \rightarrow e + \text{Ar}r^*$	0.07	$2 \times 10^{-13} \text{ m}^3\text{s}^{-1}$
7	$2\text{Ar}m^* \rightarrow e + \text{Ar} + \text{Ar}^+$	0	$6.2 \times 10^{-16} \text{ m}^3\text{s}^{-1}$
8	$\text{Ar}r^* \rightarrow \text{Ar} + h\nu$ (106.4nm)	0	106 s^{-1}
9	$\text{Ar} + \text{Ar}m^* \rightarrow 2 \text{Ar}$	0	$3 \times 10^{-21} \text{ m}^3\text{s}^{-1}$

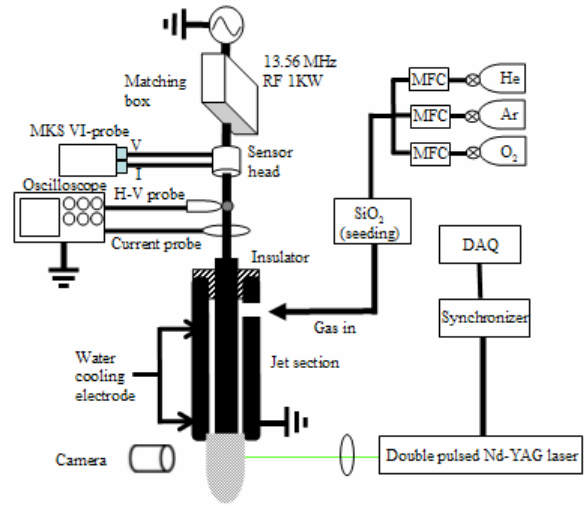


Fig. 1 Sketch of a PIV for measuring velocity distributions in the post-glow region of a co-axial APPJ.

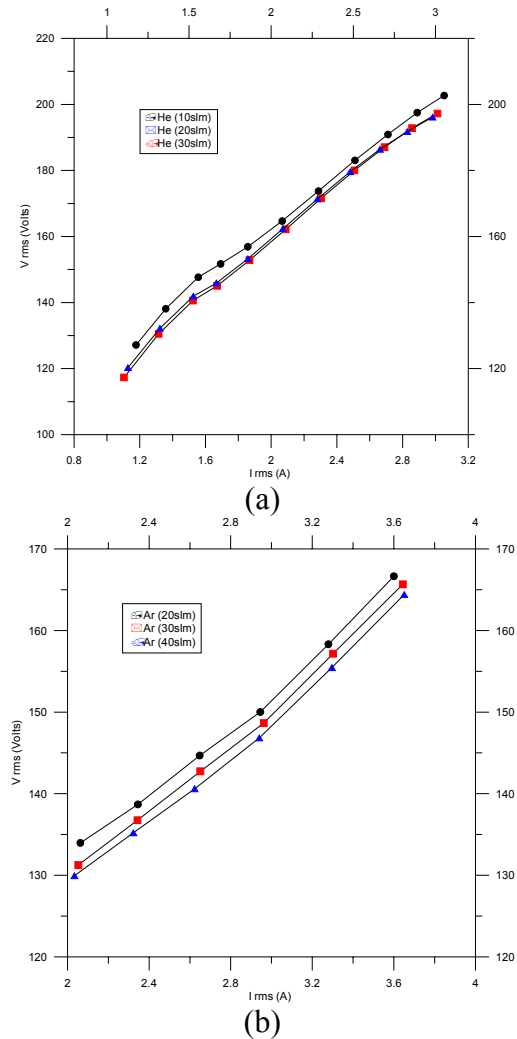


Fig. 2 Voltages as a function of current for feed gas at various flow rates. (a) pure helium, (b) pure argon.

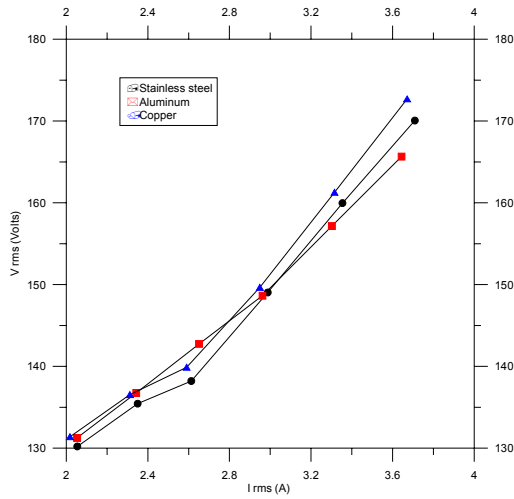


Fig. 3 Voltage as a function of current for an argon discharge at various inner electrode materials. (30 slm)

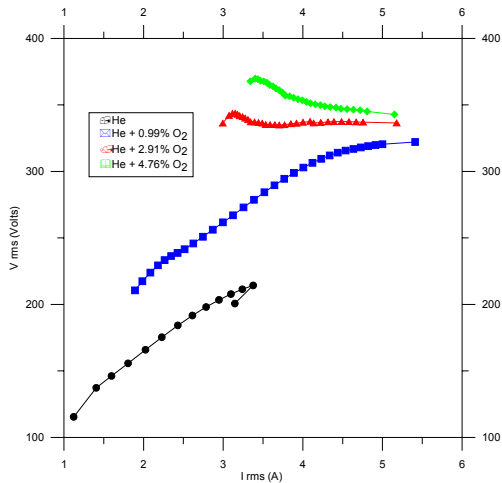
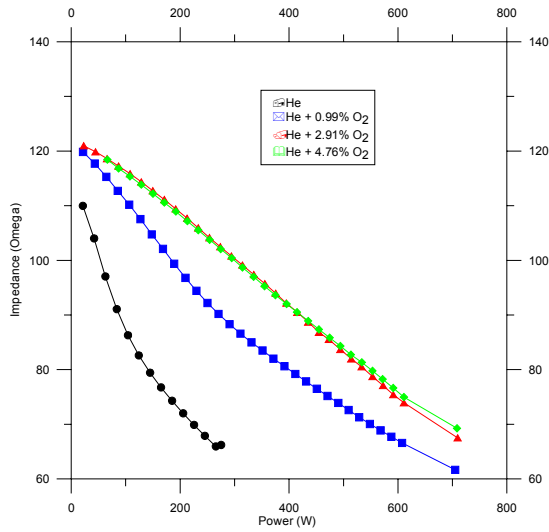
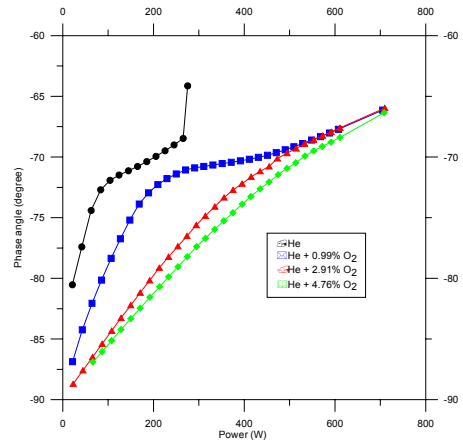


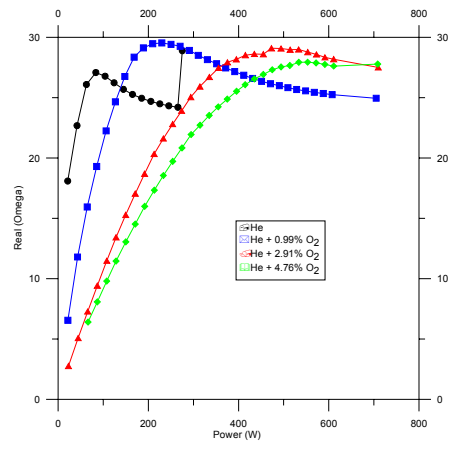
Fig. 4 Voltages as a function of current for He + O₂ feed gas at various flow rates of oxygen added at 10 slm of helium.



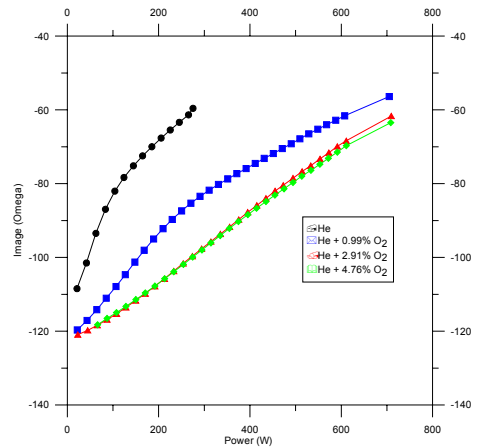
(a)



(b)



(c)



(d)

Fig. 5 The discharge data curves as a function of the input power for four different flow rates of oxygen added, 0, 0.1, 0.3 and 0.5 slm and the helium remain 10 slm: Power-Impedance curve (a), Power-Phase angle curve (b), Power-Real curve (c) and Power-Image (d).

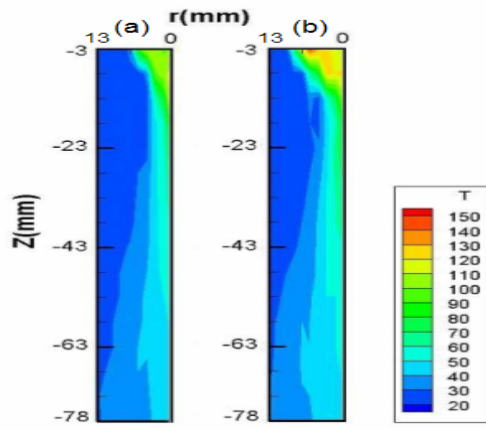


Fig. 6 Plasma temperature distribution under Ar=10slm. (a) P=120W (b) P=150W

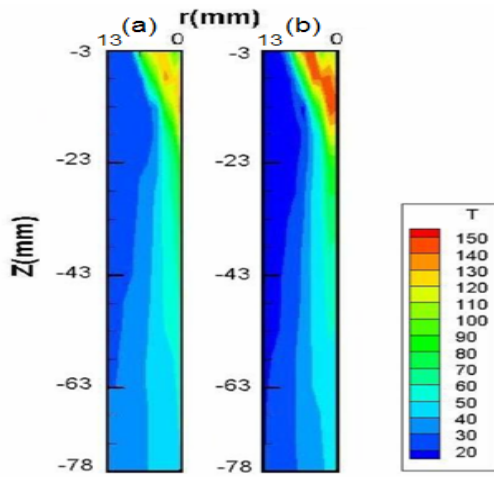


Fig. 7 Plasma temperature distribution under Ar=20slm. (a) P=120W, (b) P=150W

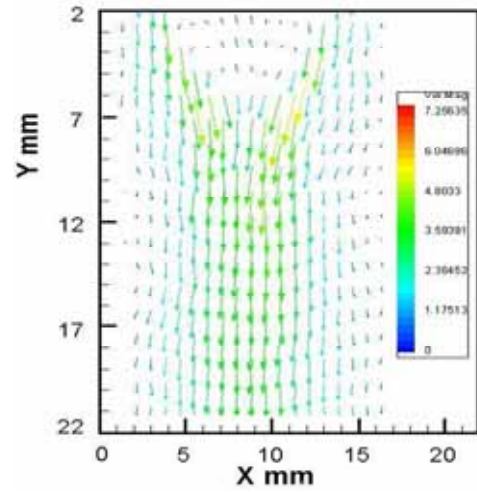
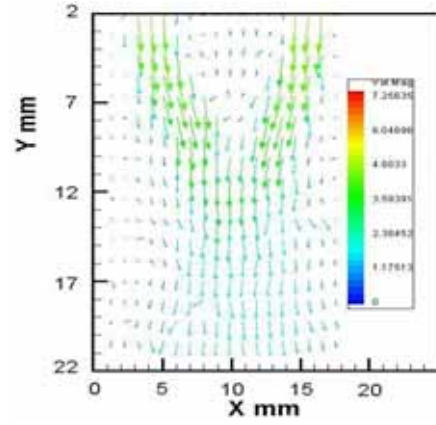
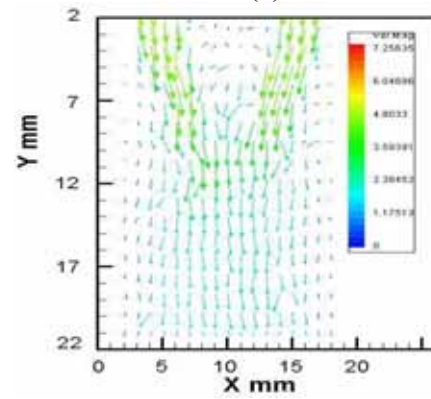


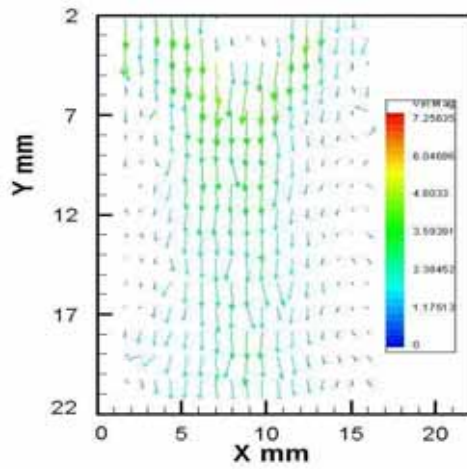
Fig. 8 Velocity distribution under variable Ar flow rate. (a) 15 slm, (b) 20 slm



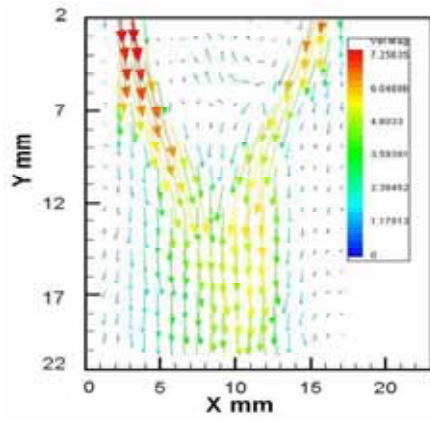
(a)



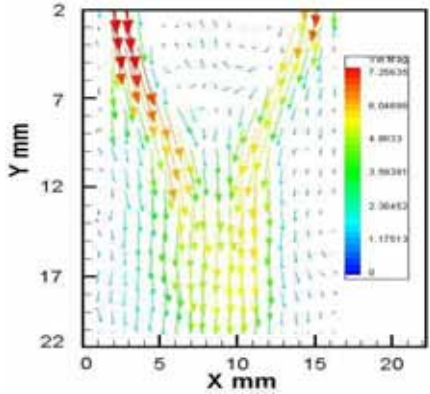
(b)



(a)

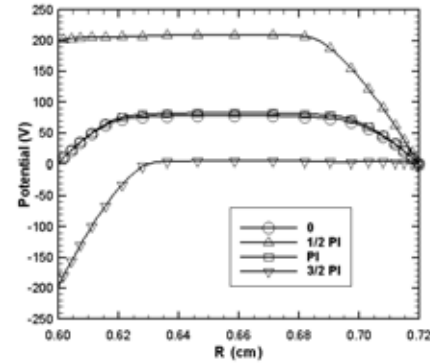


(c)

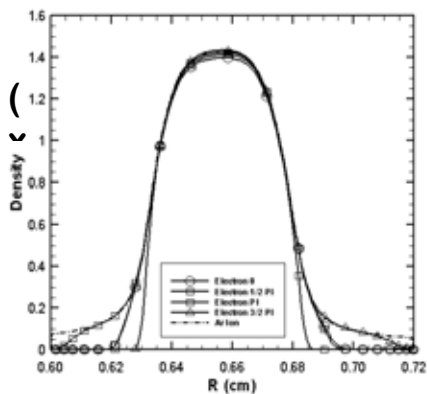


(d)

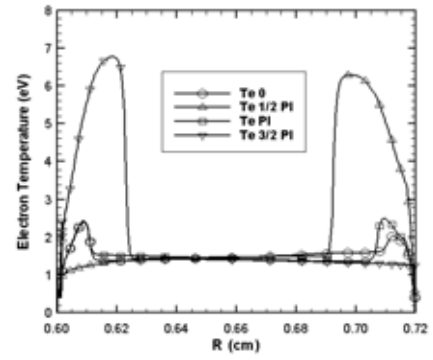
Fig. 9 Plasma velocity distribution under variable Ar flow rate and power. (a) 10 slm, 80W, (b) 10 slm, 150W, (c) 15slm, 80W, (d) 15 slm, 120W



(a)



(b)



(c)

Fig. 10 Distribution of plasma properties between electrodes at various phases of a RF cycle.

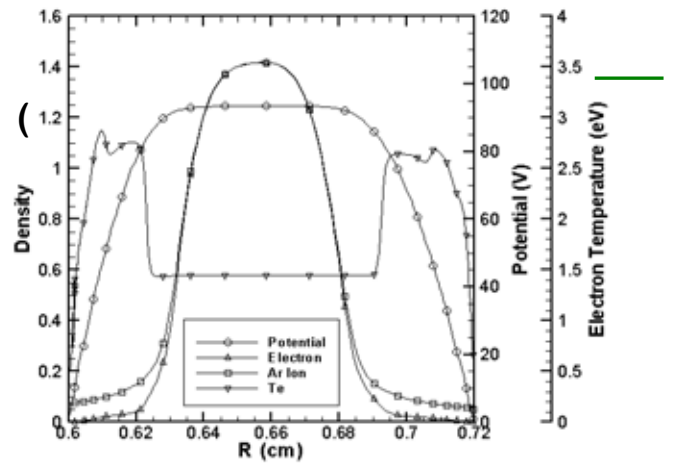


Fig. 11 Distribution of cycle-averaged plasma properties of the concentric APPJ with RF power (argon).

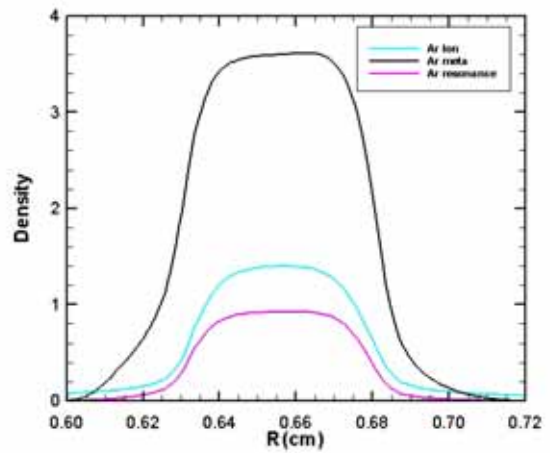


Fig. 11 Distribution of cycle-averaged densities of argon related species of the concentric APPJ with RF power (argon).