Report on Visit to University of Texas at Dallas
by International Training Program

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Recently, atmospheric pressure plasma jet (APPJ) has attracted lots of attentions for its simple configuration, no need for vacuum system and potentials for applications like biomedical treatment [1, 2]. Most APPJs have been generated in an inert gas or its mixture gas with reactive gases. For example, many researcher use helium or argon as a plasma working gas, to which a small fraction of reactive gases is added to generate chemically reactive species and avoid instabilities, especially glow-to-arc transition, leading to the filamentation of the glow discharge and the system overloading.

From the economical viewpoint, it is more desirable to use gases that are less expensive, such as N_2 or air. Recently, Kolb *et al* [3] developed a plasma jet extending to about 2 cm into ambient air in a microhollow cathode geometry for medical applications. Other devices for treating biomedical materials were presented by Hong and Uhm [4-8], which can be used to produce more than 2 cm long plasma plume by using either nitrogen or air as feed gases.

To generate after-glow plasma plume at atmospheric pressure, one vital issue is to avoid the glow-to-arc transition, because glow discharge in high pressure is prone to arc readily. Some solutions dealing with this issue are basically based on the suppression of thermal or electronic instability. Glow discharges may be sustained at atmospheric pressure by simply miniaturizing the discharge down to less than 1 mm (in the dimension of μm). Other measures, which could ease the situation, are the forced cooling of electrodes, and the use of inert gases, such as helium, argon. Furthermore, as the evolution of instabilities takes time, one could simply restrict the discharge time to a value below the time constant for instabilities. This can be achieved by pulsing the discharge. Another possibility would be to reduce the residence time of the process gas in the discharge by using high gas velocities.

The objective of this study is to develop a device capable of generating plasma jet at atmospheric pressure using N_2 or air and measure the plasma plume impedance to understand the generated plasma characteristics.

A schematic presentation of the plasma jet device is shown in Fig. 1, which consists of electrodes, dielectrics, and an AC power supply. One aluminum tube serves as an inner electrode with a 0.8 mm hole in the center. A dielectric tube made of Macor is machined for the inner electrode, into which the inner electrode is screwed. Outer electrode is a 2 mm thick aluminum disk, which is centrally perforated with a hole of 0.5 mm, through which the plasma jet is ejected to the ambient air. Two electrodes are separated by a 2 mm thick dielectric disk with a 0.8 mm hole in the center. All the parts are fixed together to prevent accidental displacements. A variac (POWERSTAT: output voltage ~ 120 V) is used as a voltage regulator and then a step-up transformer for neon light (Fransformer: peak-to-peak voltage $V_{p\text{-}p} \sim 6\sqrt{2}$ kV, $f \sim$ 60 Hz) is used to drive the plasma. Air or N_2 can be injected through the hole of inner electrode and is then ejected through the hole in the outer electrode. Once gas is introduced and high-voltage ac power is applied, a discharge is fired and a plasma jet reaching lengths up to 2 cm is ejected to the open air, as shown in the inset of Fig. 1.

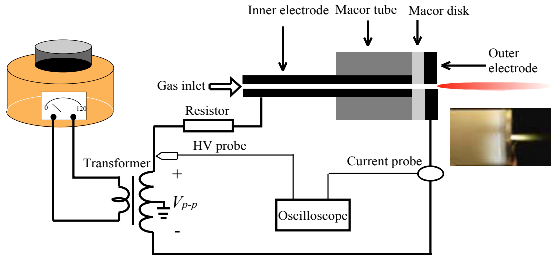

Fig.1 Schematic presentation of a plasma jet device at atmospheric pressure. The insert is the photograph of the plasma jet at 2.8 l/m N_2 flow.

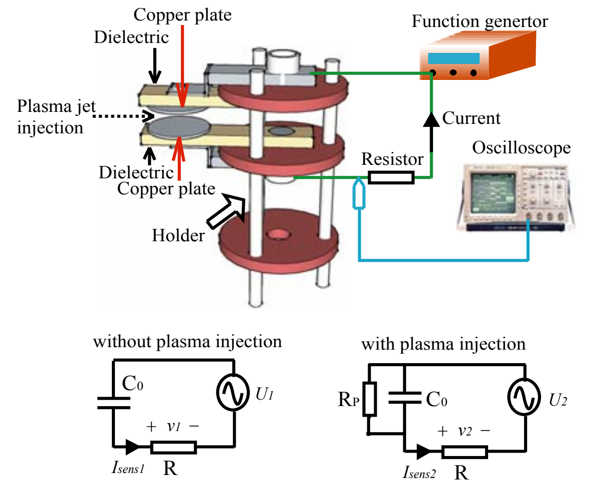

Fig.2 Setup schematic (upper) and equivalent circuit (lower) for plasma impedance measurement.

As for the impedance measurement of plasma plume, here, we consider a simple method to estimate it. Figure 2 shows the setup and equivalent circuit for plasma impedance measurement. Once plasma ignites, a plasma plume is blown out of the outer electrode and is ejected between two parallel disks with a diameter of 5 mm, which has an inherent capacitance C_0. These two disks are made of thin copper plates in order to reduce the fringe effect. The gap between them can be freely changed to facilitate measurement. A 1 MΩ resistor R is connected in series with C_0 and a sinusoidal voltage signal ($f \sim 175$ kHz, $Up\text{-}p \sim 10$ V) from function generator (Tektronix CFG250) is applied. The flowing current is obtained by measuring the voltage across R and the current variation before and after plasma injection can be used to calculate plasma plume impedance, as explained below.

The lower part of Fig. 2 shows the equivalent circuit for this measurement. For simplicity, at the point of plasma injection, we consider the plasma as a resistor R_p, which is connected in shunt with capacitor C_0. Assuming the total impedances before and after plasma injection are Z_{off} and Z_{on}, respectively, we can get the following equations, shown in Eq. (1) and (2).

$$U_1 = I_{sens1} Z_{off} = \frac{v_1}{R}\sqrt{R^2 + 1/w^2 C_0^2} \tag{1}$$

$$U_2 = I_{sens2} Z_{on} = \frac{v_2}{R}\sqrt{R^2 + \frac{2RR_p + R_p^2}{R_p^2 w^2 C_0^2 + 1}} \tag{2}$$

where C_0 is capacitance of parallel disks, v_1, v_2 are the measured voltages across resistor R before and after plasma injection, U_1, U_2 are the input voltages from function generator. During the whole measurement, we keep $U_1 = U_2$ and then we have Eq. (1) equals Eq. (2) to deduce Eq. (3). Notice that R_p should be always positive and solve this quadratic equation, we can get the R_p value, shown as Eq. (4).

$$\left(1-\frac{v_1^2}{v_2^2}\right)\left(1+R^2w^2C_0^2\right)R_p^2+2RR_p-\left[\left(\frac{v_1}{v_2}\right)^2\left(R^2+\frac{1}{w^2C_0^2}\right)-R^2\right]=0 \tag{3}$$

$$R_p = \frac{-b+\sqrt{b^2-4ac}}{2a} \tag{4}$$

where a, b and c are the quadratic coefficient, the linear coefficient and the constant term of Eq.(3), respectively.

Discharges start at about $V_{p\text{-}p} \sim 4\sqrt{2}$ kV when N_2 is used as feed gas. When increasing the voltage to around $5\sqrt{2}$ kV, a stable N_2 plasma jet can be obtained successfully. Generally, the plasma plume length largely depends on the applied voltage, flow rate and gas species. In the case of N_2, the dependence of plasma plume length on flow rate is shown in Fig.3. A maximum length of 1.7 cm is obtained with a flow rate of 6 SCFH (2.8 l/m). Also, the Reynolds number (Re) in the N_2 plasma jet device is estimated to be about 7.7×10^3 from $Re = D{\cdot}v{\cdot}\rho/\mu$, where D is the characteristic length or hole diameter, v is N_2 velocity, ρ is N_2 density (1.149 kg/m^3), and μ is N_2 viscosity (1.78×10^{-5} kg/m s) at 20 °C and at 1 atm., showing the production of N_2 plasma jet in turbulent flow. Length decreases for the cases of either lower or higher flow rate. In the former case, gas speed is not high enough to blow all the generated plasma out of discharge zone; the latter is because gas velocity is too high to form a stronger turbulent flow. We can't get a stable plasma jet when a $6\sqrt{2}$ kV voltage is applied, the discharge is confined inside rather than blown out. Reason for this is believed to be the bad machining of all parts, especially the dielectric disk. Also, when air is ejected into the inner electrode, we can't generate a stable plasma jet. Compared with N_2, discharge in air is prone to be unstable as a result of oxygen mixture. Again, the bad machining is thought to contribute to this instability.

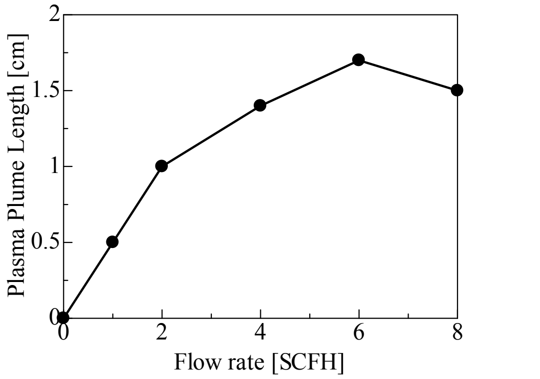

Fig.3 Dependence of visible jet length on nitrogen flow rate. $V_{p\text{-}p} \sim 5\sqrt{2}$ kV.

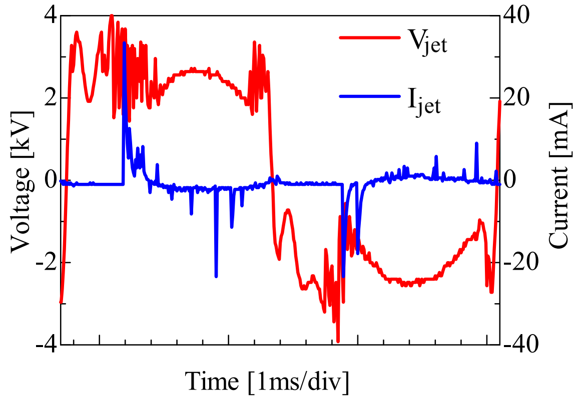

Fig.4 Waveforms of measured voltage and discharge current for this plasma jet system. N_2 flow rate: 2.8 l/m; $V_{p\text{-}p}$: $5\sqrt{2}$ kV.

The discharge voltage (V_{jet}) and current (I_{jet}) characteristics for the generator measured by a high voltage probe (Tektronix P6015) and a current monitor (Model: IPC CM-10-MG) are displayed in Fig.4 at the typical discharge conditions of N_2 flow (2.8 l/m) and $V_{p\text{-}p} \sim 5\sqrt{2}$ kV. Like pin-to-plate discharge, the current spikes erratically appear on the temporal abscissa and the average duration of these current pulses is only about hundreds of ns.

Figure 5 shows the waveforms of current I_{sens} flowing through resistor R, discharge voltage V_{jet} and current I_{jet}. It is obvious that current spikes of I_{sens} occurs at the same time of current pulses of I_{jet} ,indicating that impedance of parallel disks shown in Fig.2 changes when plasma is injected into. The current variation of I_{sens} can be used to calculate R_p, as shown in Eq.(3); however, from Fig.4, the current I_{sens} spike after plasma injection can reach as high as 80 μA, showing heavy noise may be introduced. One reason is that outer electrode is not grounded due to the limit in transformer capability. In addition, this possible noise may cause extra errors to the measurement for plasma plume impedance.

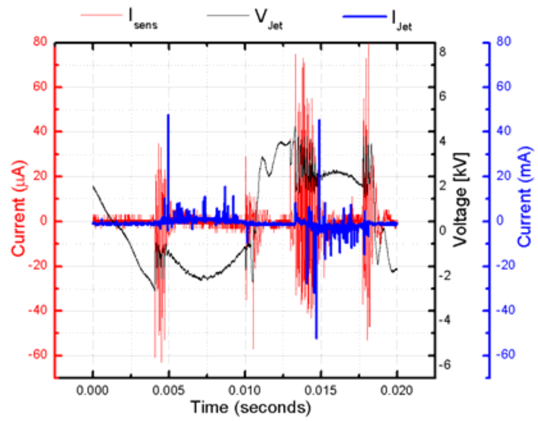

Fig.5 Measured waveforms of I_{sens}, I_{jet} and V_{jet}. Conditions: N_2 flow rate ~ 2.8 l/m; $V_{p\text{-}p} \sim 5\sqrt{2}$ kV.

Till now, we have designed and generated a N_2 atmospheric plasma jet. However, plasma plume impedance measurement remains unfinished since noise is introduced with plasma injection. In order to suppress noise, further work is planned to optimize the measurement circuit such as fringe effect reduction, grounding outer electrode and so on. Based on the present plasma jet system, detailed investigation on properties such as relationship between applied voltage, flow rate and gas species and plume length, discharge waveforms also need to be done. In addition, re-machining or redesign may be necessary to generate air plasma jet. Anyway, not only the working principle of plasma jet but also its vast applications in material processing and biomedical treatment deserve an in-depth and thorough study in future.

References

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Other things learned from this trip:

I have spent two months staying in University of Texas at Dallas and I greatly appreciate it that I was given this chance to go there. Gaining experience in UTD is quite necessary and helpful for PhD students like me. I have already learned lots of things from this trip and I have summarized them into five points, listed as follows:

1. Communicate with Professor as much as possible

I came from China and after I began my studying in Japan, I found that most of Japanese students are quite afraid of asking their professor questions. This sounds silly but it is true for many labs. After I reached UTD, I found that professors there looked like your friends and students could even tell jokes with them. In this way, students can make an easy and timely communication with their supervisors, which is better for research. Therefore, I learned that, as a PhD student, you ought to communicate with your professor as often as possible and learn from him as much as possible rather than be too afraid to ask any questions.

2. Make the best use of seminars

In UTD, we have group meetings every Wednesday and in TIT, we have seminars at the same time. By comparing these two discussions, I learned a lot. Firstly, seminar is a place not for you to keep silent but for you to raise questions, keep thinking and learning. For foreign students, bad Japanese is not an excuse to not ask questions. The important thing is to learn knowledge and don' be afraid of being mocked. In addition, seminar is also a good chance for you to realize what the other students are doing. Their research topic may be different from yours but you may be inspired by their works. Being the same lab, you are all one group. Better results may be obtained if you work with a group than that you work by yourself.

3. Cultivate your interest in research.

In UTD, what surprised me a lot is that they kept talking their experiments even at lunch time. Why are they so crazy about their research? The only answer is that they love it and then they can't help talking it. This is also one reason for their productive research. Therefore, it is better to cultivate a strong interest in your research and after doing it you will like to concentrate on your research. For example, one usually complains whenever he doesn't get good results. If he is interested in his research, he will use the time not to complain but to reconsider his experiment! This is called concentration! Anyway, cultivating strong interests in research is quite important for PhD students.

4. Be active

This point is not only helpful for research but also for one's life: be active and don't be shy. In UTD, I have saw lots of active PhD students and they really impressed me. Of course, because of the cultural difference, Americans are prone to be active. However, as my professor Dr. Overzet said, your life state will definitely affect your research state. This is easy to understand if you consider that PhD students spend lots of time on research and in some way, research is kind of their life. So, for your research and your life, I think being an active person is better.

5. Prepare for the life after graduation

During the time in USA, I have made many American friends, mostly PhD students and also met with some friends I have already known when I was in China. I am really impressed with their enthusiasm and optimism. Life is not a smooth journey and sometime there will be difficulties, hardships and even bad things. For PhD students who will spend lots of precious time on research, conducting research is not all what they should do. They also should learn something for their life after graduation, which are equally important.

All in all, I have learned and experienced lot about research methods and lifestyles in UTD, which will be helpful for both my research and my future development. And as a saying goes, easier said than done, I will conduct these principles for my future research and life.