Advance on non-equilibrium plasma jets

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Outline

- Overview of the status of Cold Plasma Jets
- Recent Progress on plasma jet research in our lab
  - A single electrode plasma jet device
  - A comparative analysis of a pulsed dc and ac excited plasma plume
  - A RC plasma jet driven by pulsed DC
  - A RC air plasma jet driven by pulsed DC
  - A self-pulsed air plasma needle
  - Plasma jet array
Overview of the status of Cold Plasma Jets

- RF Hicks group, 1998 Plasma Sources Sci. Technol. 7 286-8
- Gas temperature can be as low as tens of Celsius degree.
- The risk of arcing exists.

- Gas temperature is sensitive to the distance from the needle tip. It can be at room temperature.
Gas temperature is quite high. It can be touched by a finger for few seconds.

The jet consumes power of about 4 W at peak voltage of 7 kV and frequency of 13 kHz.

The jet looks continuously by bare eye is actually travels like a bullet with a velocity of 15 km/s.
When $N_2$ is flow from the back and a 20 kHz high voltage is applied between the two electrodes, a plasma jet up to 6.5 cm is generated in the surrounding air.

Diameter of the hole is about 500 $\mu$m.

The plasma is driven by pulsed DC voltage. It can have a length of about 5 cm.


Driven by pulsed DC high voltage, pulse frequency: 1 kHz; amplitude 6 kV.


Applied voltage 134.7 kHz; $V_{pp}$ is less than 600 V; working gas Ar.

- Applied voltage 48 kHz; working gas Ar.


- Ar is fed through the side arm of the tube, and O₂ is injected into the end of quartz tube through the inner electrode to react with Ar plasma.
- Electron attachment inside the tube is weakened.

Applied voltage 20 kHz; working gas Helium. The plasma jet was used in combination with H$_2$O$_2$ to remove stains from teeth stained by either coffee or red wine.


Applied voltage 1 kHz; working gas N$_2$


DC voltage; working gas Air.

Applied voltage 60 Hz; working gas Air.
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A single electrode plasma jet device

Pulse Generator
Amplitude: up to 10 kV
Pulse width: 200 ns to DC
Repetition rate: up to 10 kHz

Geometry
Nozzle: Φin=1.2 mm
Syringe: Φin=6mm
Quartz tube: Φin=2mm
Φout=4mm

Two discharge current pulses per applied voltage pulse

The discharge current is on the order of several hundreds mA

The current carried by the plasma plume is slightly smaller than the discharge current
Effect of repetition frequency on current

The higher the repetition frequency, the early the current appears.

Rotational and vibrational temperature

♥ A finger can touch any part of the plasma plume without any feeling of electrical shock or warmth at all.

♥ The rotational and vibrational temperatures of the plasma plume are about 300K and 2950K, respectively.
Setup of Plasma relay

Experimental setup

Photograph of plasma relay

Photograph of the plasma
The primary plasma disappears before the secondary plasma starts to propagate.

The propagation velocity of the primary plasma is several times higher than that of the secondary plasma.
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A comparative analysis of a pulsed dc and ac excited plasma plume

(a) Setup; (b) AC driven ($V_{pp}=16$ kV) and (c) Pulsed DC driven ($V=8$ kV, pulse width 800 ns. Both frequency 4 kHz, He flow rate 2 l/min.

$P_{\text{pulse}}=1.8$ W, $P_{\text{ac}}=3.5$ W.

Emission spectra for Pulsed DC and AC

(a) Pulsed

(b) AC

- 777.3 nm: O(3p^5P–3s^5S)
- 728.1 nm: He(3^1S–2^1P)
- 706.5 nm: He(3^3S–2^3P)
- 667.8 nm: He(3^1D–2^1P)
- 587.5 nm: He(3^3D–2^3P)
- 501.5 nm: He(3^1P–2^1S)
- 522.7 nm: N_2^+(B^2^Σ_u^+–X^2^Σ_g^-)

- 309.0 nm: OH(A^2^Σ_u^+–X^2^Σ_g^-)
- 380.4 nm
- 375.4 nm
- 371.0 nm
- 357.6 nm
- 353.6 nm
- 337.1 nm
- 315.8 nm

(c) Intensity (a.u.)

(d) Intensity (a.u.)

Wavelength (nm)
Rot. and Vib. Temperature for Pulsed and AC

Gas temperature

Vibrational temperature
Decontamination effect for Pulsed DC and AC

Control (a) (c) Pulsed

Control (b) (d) AC

Control Direct Indirect
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A RC plasma jet driven by pulsed DC voltage

Schematic of the device

Photograph of the device

Plasma plume photo

Plasma in a tooth

Plasma touched by a finger
The displacement current waveform behaves as that of a typical RC charge and discharge circuit.

The actual discharge current has a peak value of about 10 mA.

The voltage on the needle has a peak of about 6 kV.

The power deposited into the plasma is estimated to be less than 0.1W.
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A RC air plasma jet driven by pulsed DC

Photograph of the plasma
IV of the plasma

(a) I-V characteristic of the plasma. $V_1$, $V_2$, and $V_3$ are the voltages at three different locations. $I$ is the discharge current. (b) Zoom in the first three discharge current spikes $I$ and $V_3$.

♥ Several current spikes appear periodically for one voltage pulse. ♥ When the voltage applied on the needle reaches about 1.5 kV, the first discharge appears and the first current spike has a peak value of more than 1.5 A with a pulse width of about 10 ns. The following current spikes have a peak value of about 0.5 A.
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Setup of the device
The gas temperature of the plasma remains at room temperature.
The discharge actually appears periodically with a frequency of about 30 kHz.

The repetition frequency does not strongly depend on the applied voltage.
Discharge current for various gap distance

With the increase of the gap distance, the pulse repetition frequency decreases significantly.

The peak values of the discharge currents have no big difference for the three gap distances.

Although the peak value of the discharge current is quite high, the pulse width of the current is only about 100 ns.
Emission spectra of the plasma

♥ the spectrum is dominated by N₂ emission. Moreover, there is also O-atom emission.
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Photograph of the plasma jet array
Dynamics of the plasma jet array

- The plasma plumes on both edges initiate early than that in the middle of the plasma array.
- The propagation speed of the plasma plume on both edges is higher than that in the middle of the plasma array.
The electric field on both edges is higher than that in the middle of the plasma array.

The differences of the dynamics of the plasma plumes is probably due to the electric field distribution of the plasma array.
Summary

- Because of their capability to generate plasmas that are not spatially bound or confined by electrodes, atmos. Pres. Non-equilibrium plasma jets are attracting lots of attentions in various applications.

- Not only room temperature noble gas plasma jets can be generated at surrounding air, but also room temperature air plasma can be generated.
Thank You!