Nanosecond-scale Processes in a Plasma Pilot for Ignition and Flame Control

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Outline of the presentation

• Introduction and statement of problem
• Non-steady state nanosecond scale processes in a gap with absence of constrained gas flow
• Non-steady state behaviour of the discharge in plasmatron-type system with external gas flow
• Features of the discharge in ignition unit of Tornado system
• Conclusion
Exit aperture: $\varnothing$ 4-5 mm; Gas flow: $G = 0.1-1.5$ g/s; $C = 100-300$ pF

Most investigators speak of averaged electrical parameters of discharge

Averaged electrical parameters: $i_d \leq 0.3$ A, $V_d \geq 500$ V, $Q_d < 300$ W

With a low current this approach is incorrect in principle.
Principal physical idea for interpretation of the discharge burning modes in plasmatron

Essential role of non-steady state discharge phenomena in the processes of combustion initiation and flame stabilization

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- Glow-type discharge in plasmatron is accompanied by so-called glow-to-spark transition process. As a result the high-current nanosecond spark discharge pulses are superimposed on the low-current background glow discharge

- Energy to the nanosecond spark discharge is delivered from the capacitance of connecting cable $C$

- The above regime is most efficient both for ignition and flame control
Example of regime for the plasmatron operation in air-propane mixtures

\[ G(\text{air}) = 0.45 \text{ g/s}, \ i_d = 84 \text{ mA}, \ V_d = 630 \text{ V}, \ Q_d = 53 \text{ W}, \ W_d = 120 \text{ J/g}, \ \Delta T = 115 \text{ K} \]

<table>
<thead>
<tr>
<th>( G ) (propane), g/s</th>
<th>( \alpha )</th>
<th>( i_d ), mA</th>
<th>( V_d ), V</th>
<th>( Q_d ), W</th>
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\[ G(\text{air}) = 0.75 \text{ g/s}, \ i_d = 84 \text{ mA}, \ V_d = 840 \text{ V}, \ Q_d = 70 \text{ W}, \ W_d = 95 \text{ J/g}, \ \Delta T = 90 \text{ K} \]

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<td>0.12</td>
<td>0.4</td>
<td>84</td>
<td>980</td>
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Averaged increase in temperature is extremely low \( \Delta T \approx 100 \text{ K} \)
However the burning is initiated and sustained in a wide range of \( \alpha \) (air to fuel ratio)
Voltage at the gap of plasmatron illustrating the non-steady state behavior of the discharge at a low average current $i_d = 80$ mA.

The further presentation is actually an interpretation of the non-steady state discharge behavior.
Experimental arrangement for the discharge investigation with a nanosecond time resolution in a gap with absence of constrained gas flow

Generator of nanosecond pulses based on coaxial lines

\[ C_1 \text{ is the filtered capacitor of power supplier} \]

Interelectrode distance \( d = 0.2 \text{ mm, } p = 2 \text{ atm (nitrogen)} \)
\[ R = (20-155) \text{ k}\Omega, \; C = 40 \text{ pF} \]

Essence of the experiments

- Recording the current and voltage waveforms with nanosecond time resolution
- Recording extremely low current at the stages of decayed plasma after a spark discharge
Voltage and current for the case when discharge gap does not completely recover its dielectric strength

In pause between pulses plasma from a preceding spark is still available in the gap

\[ R = 155 \text{ k}\Omega, \quad C = 40 \text{ pF} \]

Single pulse of the spark channel with nanosecond time resolution
Formation of the spark channel in decayed plasma

\[ R = 89 \, k\Omega, \quad V_A = 1.7 \, kV \]

\[ R = 89 \, k\Omega, \quad V_A = 2.8 \, kV \]

To increase \( V_A \) means to increase a current in a pause between pulses
Temporal stages of the discharge:

*arc discharge with cathode spot and spark formation in decayed plasma*

\[ R = 20 \text{ k}\Omega, \ V_A = 2.25 \text{ kV} \]

Arc cathode spot is not able to be sustained for a long time
Temporal stage of the discharge: 
*glow discharge, glow-to-spark transition*, and *glow discharge*

\[ R = 20 \, \text{k}\Omega, \, V_A = 2.4 \, \text{kV} \]
Temporal stages of the discharge: glow discharge, glow-to-spark transition, and spark in the decayed plasma

\[ R = 20 \, \text{k}\Omega, \quad V_A = 2.4 \, \text{kV} \]
Glow-to-spark transition. What is it?

Summary of preceding data on constriction of glow discharge in gas lasers


Parameters of the glow discharge
\[ d = 0.7 \text{ cm}, j = 500 \text{ A/cm}^2, p = 75 \text{ Torr} \]

\textit{Glow-to-spark transition (temporal stages)}

1 - Glow type discharge
2, 3, 4 - Arising of a cathode spot and attachment of a \textit{diffused channel} to the spot (glow-to-spark transition is not completed yet)
5, 6 – Propagation of a \textit{high-conductivity filamentary spark channel} along the diffused channel
The slides below are experimental data for discharge in plasmatron with external air flow

Exit aperture: $\varnothing$ 4-5 mm; Gas flow: $G = 0.1$-$1.5$ g/s; $C = 100$-$300$ pF
Temporal measurements of current and voltage with nanosecond time resolution
Illustration of very first breakdown in plasmatron

- Oscillatory behavior of the current when spark discharge occurs
- High-conductivity spark channel forms in the gap

\[ G = 0.1 \text{ g/s (} v_{\text{gas}} = 4 \text{ m/s)} \]
\[ R_b = 13.6 \text{ k\Omega}, \quad C = 300 \text{ pF} \]
\[ V_0 = 2.7 \text{ kV} \]

- Spark current \( i = 30 \text{ A} \)
- Current after discharging the capacitor \( C \) is limited by ballast resistor (\( i \approx 200 \text{ mA} \)
What happens in the gap after the very first breakdown

- **First stage:** Discharge current is gradually shifted from coaxial part of the cathode to the end part of the cathode
  
  *glow-type discharge and glow-to-spark transitions (completed and non-completed)*

- **Second stage:** Discharge current is attached to the end part of the cathode
  
  *glow-type discharge and glow-to-spark transitions (completed and non-completed)*

\[ G = 0.1 \, \text{g/s} \ (v_{\text{gas}} = 4 \, \text{m/s}) \]

\[ R_b = 13.6 \, \text{k}\Omega, \ C = 300 \, \text{pF} \]

\[ V_0 = 3.2 \, \text{kV} \]

\[ V_{\text{first}} \approx 350 \, \text{V} \]

\[ V_{\text{second}} \approx 1200 \, \text{V} \]
What happens in the gap after the very first breakdown (more detailed waveforms)

\[ G = 0.1 \text{ g/s} \ (v_{\text{gas}} = 4 \text{ m/s}) \]

\[ R_b = 13.6 \text{ k}\Omega, \ C = 300 \text{ pF} \]

\[ V_0 = 3.2 \text{ kV} \]

- **First stage:** Discharge is attached to coaxial part of the cathode

  *(glow-type discharge and transitions to diffused channel regimes)*
Discharge is attached to the end of the cathode (second stage)

- Glow-type discharge is accompanied by glow-to-spark transitions
- In most cases the transition is not completed (the high conductivity spark channel does not form)

\[ G = 0.1 \, \text{g/s} \quad (v_{\text{gas}} = 4 \, \text{m/s}) \]
\[ R_b = 13.6 \, \text{k\Omega}, \quad C = 300 \, \text{pF} \]
\[ V_0 = 3.0 \, \text{kV} \]

Plasma torch is available at the exit of plasmatron

Average power dissipated in the torch is about 150 W
Illustration of the voltage and current for non-completed transition from glow to spark

- Resistance of the diffuse channel is much higher than impedance of $LC$ circuit
- Discharge current has aperiodic form

$G = 0.1 \text{ g/s (} v_{\text{gas}} = 4 \text{ m/s)}$

$R_b = 13.6 \text{ k}\Omega$, $C = 300 \text{ pF}$

$V_0 = 3.0 \text{ kV}$
Illustration of the voltage and current for completed transition from glow to spark

- Resistance of the spark channel is much less than impedance of LC circuit
- Capacitance is discharged completely

\[ R_b = 54 \, \text{k}\Omega, \quad C = 460 \, \text{pF} \]
\[ V_0 = 3.0 \, \text{kV} \]
Illustration of the voltage and current for completed transition from glow to spark

- Resistance of the spark channel is much less than impedance of $LC$ circuit
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Illustration of the voltage and current for completed transition from glow to spark

- Resistance of the spark channel is much less than impedance of LC circuit
- Capacitance is discharged completely

\[ R_b = 54 \text{ k}\Omega, \quad C = 460 \text{ pF} \]
\[ V_0 = 3.0 \text{ kV} \]
End-on CCD frames of discharge image for different times (diffused channels)

\[ G = 0.1 \text{ g/s (} v_{\text{gas}} = 4 \text{ m/s)} \]

\[ R_b = 13.6 \text{ k}\Omega, \ C = 300 \text{ pF} \]

\[ V_0 = 3.0 \text{ kV} \]
$G = 0.5 \text{ g/s (} v_{\text{gas}} = 20 \text{ m/s)}$

$R_b = 13.6 \text{ k}\Omega, C = 300 \text{ pF}$

$V_0 = 3.0 \text{ kV}$

- Glow-to-spark transition process is expressed distinctively. Spark channel results in complete discharging of the capacitance $C$
Discharge is attached to the end of the cathode (second stage)

Gas flow is increased up to 0.5 g/s

\[ G = 0.5 \text{ g/s} \quad (v_{\text{gas}} = 20 \text{ m/s}) \]

\[ R_b = 13.6 \text{ k}\Omega, \quad C = 300 \text{ pF} \]

\[ V_0 = 2.5 \text{ kV} \]

Plasma torch is still available at the exit of plasmatron

- Glow-to-spark transition process is expressed distinctively
- In some cases discharge at the end of the cathode is extinguished and new breakdown occurs at a coaxial part of the cathode
Illustration of very first breakdown in plasmatron

*Gas flow is increased up to 1.0 g/s*

$G = 1.0 \text{ g/s (} v_{\text{gas}} = 40 \text{ m/s)}$

$R_b = 13.6 \text{ k}\Omega, \ C = 300 \text{ pF}$

$V_0 = 3.1 \text{ kV}$

- The same features of the discharge as for a low gas flow
What happens in the gap after the very first breakdown

- Increasing the gas flow leads to reducing the first stage of the discharge

\[ G = 1.0 \text{ g/s (} v_{\text{gas}} = 40 \text{ m/s)} \]
\[ R_b = 13.6 \text{ k} \Omega, \ C = 300 \text{ pF} \]
\[ V_0 = 3.0 \text{ kV} \]
Discharge is attached to the end of the cathode (second stage)

*Gas flow is increased up to 1.0 g/s*

\[ G = 1.0 \text{ g/s} \quad (v_{\text{gas}} = 40 \text{ m/s}) \]

\[ R_b = 13.6 \text{ k}\Omega, \quad C = 300 \text{ pF} \]

\[ V_0 = 3.0 \text{ kV} \]

- Glow-to-spark transition process is expressed extremely distinctively
- In some cases discharge at the end of the cathode is extinguished and new breakdown occurs at a coaxial part of the cathode

200-1200 µs
Current for the case of completed transition from glow to spark

$G = 1.2 \text{ g/s} \ (v_{\text{gas}} = 50 \text{ m/s})$

$R_b = 13.6 \text{ k}\Omega, \ C = 300 \text{ pF}$

$V_0 = 3.0 \text{ kV}$

- Oscillatory behavior of the current when glow-to-spark transition spark occurs
- High voltage probe does not reflect the voltage waveform with nanosecond time resolution

Spark channel
Current for the case of non-completed transition from glow to spark

- Aperiodic behavior of the current when glow-to-spark transition spark occurs
- Resistance of the diffuse channel is comparable with impedance of $LC$ circuit

$G = 1.2 \text{ g/s (} v_{\text{gas}} = 50 \text{ m/s)}$

$R_b = 13.6 \text{ k}\Omega$, $C = 300 \text{ pF}$

$V_0 = 3.0 \text{ kV}$
Design of the trigger unit for the Tornado chamber

gas flow
anode
cathode
Voltage and current for different gas flows in trigger unit of the Tornado chamber

For $G = 0.2 \text{ g/s}$:

- $R_b = 13.6 \text{ k}\Omega$
- $C = 300 \text{ pF}$
- $V_0 = 4 \text{ kV}$

For $G = 1.5 \text{ g/s}$:

- $R_b = 13.6 \text{ k}\Omega$
- $C = 300 \text{ pF}$
- $V_0 = 4 \text{ kV}$
End-on CCD frames of the discharge image for different times and gas flows

1. $G = 0.2 \text{ g/s}, \ t_{\text{exp}} = 40 - 50 \text{ ms}$

2. $G = 1.5 \text{ g/s}, \ t_{\text{exp}} = 10 - 20 \text{ ms}$

3. $G = 1.5 \text{ g/s}, \ t_{\text{exp}} = 30 - 40 \text{ ms}$

4. $G = 1.5 \text{ g/s}, \ t_{\text{exp}} = 60 - 61 \text{ ms}$
Conclusion

• Glow-type discharge in plasmatron is accompanied by so-called glow-to-spark transition process. As a result the high-current nanosecond spark discharge pulses are superimposed on the low-current background glow discharge.

• Energy to the nanosecond spark discharge is delivered from the spurious capacitance of connecting cable $C$.

• The above regime is most efficient both for ignition and flame control.