Thermal perturbations
generated by near-surface electric discharges
and mechanisms of their interaction with the airflow

I.V. Adamovich¹, S.B. Leonov², K. Frederickson¹,
J.G. Zheng³, Y.D. Cui³, and B.C. Khoo³

¹ Department of Mechanical and Aerospace Engineering, Ohio State University
² Department of Aerospace and Mechanical Engineering, University of Notre Dame
³ Temasek Laboratories, National University of Singapore
I. Background / Introduction

II. Kinetics of energy transfer and thermal perturbations in surface and volumetric ns pulse discharges

III. Effect of localized heating on formation of flow structures, implications for high-speed plasma flow control

IV. Effect of accelerated vibrational relaxation on nonequilibrium flow field, implications for high-speed flow control

V. Summary and future outlook
I. EHD body force

- Coulomb force interaction in AC DBD discharges: neutral flow entrainment by ions. Low-speed boundary layer flow separation control.

II. Repetitive Localized Heating

- Localized arc filament plasma actuators (LAFPA): inducing flow instabilities. Effective at low actuator powers, up to $M=0.9-2.0$

- Ns pulse surface plasma actuators (NS-DBD): coherent structures formation, boundary layer reattachment in low-temperature, ns pulse plasmas (up to $M=0.3$)

Goal

High-speed flow control at low energy cost, over a wide range of flow geometries, Mach and Re numbers: boundary layer transition and separation, shock wave control, drag reduction, mixing enhancement
Schlieren visualization of a NS-DBD plasma actuator operated in quiescent air

• Heating in the discharge: compression wave formation on μs time scale
• Residual heating: late small-scale random perturbations on ~ 0.1-1 ms time scale
• What are the kinetics involved? Which one is important for plasma flow control?

Schlieren visualization of a NS-DBD plasma actuator operated in quiescent air

Temperature dynamics in volumetric ns pulse discharge filament in air (P=100 Torr)

t= 1-10 μs (frames are 1 μs apart)

Montello et al, J. Fluid Science and Technol., 2013
Energy transfer and temperature dynamics in discharge and afterglow in air are well understood.

- TV rise in early afterglow: V-V exchange, \( \text{N}_2(v) + \text{N}_2(v=0) \rightarrow \text{N}_2(v-1) + \text{N}_2(v=1) \)
- TV decay in late afterglow: V-T relaxation, \( \text{N}_2(v) + \text{O} \rightarrow \text{N}_2(v-1) + \text{O} \)
- “Rapid” heating: quenching of \( \text{N}_2 \) excited electronic states, \( \text{N}_2^+ + \text{O}_2 \rightarrow \text{N}_2(X) + \text{O} + \text{O} \)
- “Rapid” heating: pressure overshoot on centerline, compression wave formation
- “Slow” heating: V-T relaxation, \( \text{N}_2(X,v) + \text{O} \rightarrow \text{N}_2(X,v-1) + \text{O} \)
- “Slow” heating: affecting “late” random perturbations

Mechanism of accelerated “slow” heating:

- V-V energy exchange between N$_2$ and CO$_2$(v$_3$) mode: N$_2$(v=1) + CO$_2$(000) $\leftrightarrow$ N$_2$(v=0) + CO$_2$(001)
- CO$_2$ energy re-distribution among vibrational modes: CO$_2$(001) + M $\leftrightarrow$ CO$_2$(100,020,010) + M
- V-T relaxation of bending mode: CO$_2$(010) + M $\rightarrow$ CO$_2$(100) + M
- Heating by accelerated vibrational relaxation may be used for nonequilibrium flow control

Frederickson et al, Plasma Sources Sci. Technol., 2017
Localized Arc Plasma Flow Actuators (LAPFA):
Exciting instabilities in transonic and supersonic flows (M=0.9-2.0)

- Circular nozzle, 1 inch diameter
- Arc filament discharge pulses, ~10 μs
- Multiple channels controlled by fast HV switches
- Independent control of frequency, phase, and duty cycle → excitation of different instability modes

Samimy et al, AIAA J., 2007
LAPFA: Formation of spanwise vortices in a M=0.9 circular jet

- High amplitude perturbations (localized heating in arc filaments)
- Every discharge pulse results in vortex formation
- Flow responds to forcing near jet column instability frequency

Kim et al, Expts. Fluids, 2010
• Every nanosecond discharge pulse produces a spanwise vortex

• Qualitatively similar to LAFPA actuators

• Enhanced mixing with free stream → boundary layer reattachment

• Same effect detected up to $u=96 \text{ m/sec}$ ($M=0.28, \text{Re}_x \sim 1.5 \cdot 10^6$)

Little et al, AIAA J., 2012
**Spanwise vortex dynamics: high-speed schlieren**

(Tohoku University, Japan)

- $U = 20 \text{ m/s}, \ \text{AoA} = 22^\circ, \ f = 3 \text{ kHz} (\tau = 0.33 \text{ ms})$
- Compression waves are seen in 0.7 ms image only, others are “between the frames”
- No evidence of compression wave on flow structure (compare images at 0.6 ms and 0.7 ms)
- Every discharge pulse generates an individual vortex, all vortices appear to rotate clockwise
- Vortices #1 and #2 travel above the separation zone, all subsequent vortices follow the surface

Komuro et al, 68th GEC, 2015
PIV measurements and plasma / CFD modeling: (National University of Singapore, AIAA Papers 2017-0712, 0715)

- Objective: obtain quantitative insight into the mechanism of plasma flow control

Baseline flow (without control): \( \text{Re} = 0.05 \cdot 10^6 \ (U_\infty = 10 \text{ m/s}), \quad \text{AoA} = 15^\circ \)

Ns pulse surface ionization wave plasma / volumetric residual heating model

(Takashima et al., Plasma Sources Sci. Technol. 2013)

Coupled with 2-D compressible flow Navier-Stokes equations

Are spanwise vortices formed by compression waves?

Numerical schlieren images overlaid with streamlines:

Compression wave propagation through the external flow

$$\text{Re} = 0.05 \cdot 10^6 \ (10 \text{ m/s}), \ \text{AoA} = 15^\circ, \ U_p = 20 \text{ kV}, \ f = 0.15 \text{ kHz}, \ f^+ = 1.2$$

Effect of compression wave on external flow is very weak

Are spanwise vortices formed by residual heating?

Numerical schlieren images overlaid with streamlines:

Re = 0.05 \cdot 10^6 (10 \text{ m/s}), \ AoA = 15^\circ, \ U_p = 20 \text{ kV}, \ f = 0.15 \text{ kHz}, \ f^+ = 1.2

Generation of a spanwise vortex by residual heating after the first discharge pulse (via inviscid instability)

Experimental (PIV) data
Baseline and forced flows, Re = 0.05 \cdot 10^6

Spanwise vortex formation, flow reattachment begins after the first discharge pulse

Plasma / CFD predictions
Baseline and forced flows, $Re = 1.2 \cdot 10^6$

Residual heating after every discharge pulse results in a spanwise vortex formation

$Re=1.2\times10^6$: $U_\infty=93\text{ m/s}$, $c=20.32\text{ cm}$, $\alpha=20^\circ$
Comparison between PIV data and CFD predictions:

\[ \text{Re} = 0.05 \cdot 10^6 \]

Results compared after \( N_p = 1, 2, \) and 3 discharge pulses: good qualitative agreement

Using accelerated relaxation of vibrational energy to control supersonic mixing / shear layer

- Plenum: overlapped ns pulse / DC sustainer discharge for vibrational loading of N$_2$
- P$_0$ = 300 torr, T$_V$=2000, T=500 K, 2-D nozzle, top wall contoured, bottom wall plane
- Condition at nozzle exit: M = 2.5, P$_{\text{exit}}$ = 15 torr
- Subsonic flow below expansion corner: injection of N$_2$ or CO$_2$
- Optical access for schlieren, CARS, and NO PLIF in subsonic and supersonic flows

Nishihara et al, AIAA Paper 2015–0577
Frederickson et al, Plasma Sources Sci. Technol., 2017
Effect of vibrational relaxation of shear layer: 
\( \text{N}_2 / \text{N}_2 \) (left) vs. \( \text{N}_2 / \text{CO}_2 \) (right)

- Time delay between frames 5 ms, \( t = 0-80 \) ms
- \( \text{Ns pulse/DC discharge (2.3 kW)} \) is turned on at \( t = 10-45 \) ms, to excite main \( \text{N}_2 \) flow
- No perturbation of shear layer detected in \( \text{N}_2 / \text{N}_2 \) flow
- In \( \text{N}_2 / \text{CO}_2 \) flow, shear layer expansion angle decreases, approaching \( \theta = 0^\circ \)
- No change observed if main \( \text{N}_2 \) flow is not excited

\[ \text{N}_2 \text{ “bleeding” through backstep} \quad \text{CO}_2 \text{ “bleeding” through backstep} \]

\[ \text{Nishihara et al, AIAA Paper 2015–0577} \]
\[ \text{Frederickson et al, Plasma Sources Sci. Technol., 2017} \]
Top flow: vibrationally excited N\textsubscript{2}, \(T_v=1900\) K, estimated \(T_{rot}=240\) K

Bottom flow: CO\textsubscript{2} bleeding through backstep, static pressure 7 torr

CO\textsubscript{2} bleeding reduces \(T_v(N_2)\), increases \(T_{\text{trans/rot}}\) and static pressure

Consistent with time-resolved measurements in ns pulse discharge in quiescent N\textsubscript{2}-CO\textsubscript{2}

Static pressure increase pushes up shear / mixing layer

Nishihara et al, AIAA Paper 2016–1762

Frederickson et al, Plasma Sources Sci. Technol., 2017
Summary

• Surface and volumetric ns pulse discharges:
  ➢ Rapid energy thermalization on sub-acoustic time scale, high-amplitude compression wave generation
  ➢ Residual heating affected by slow energy thermalization dominated by vibrational relaxation
  ➢ Kinetics of energy thermalization ("rapid" and "slow" heating) is well understood
  ➢ Dynamics of small-scale random perturbations, their potential for flow control remain uncertain

• NS-DBD surface plasma actuators
  ➢ Compression waves have almost no effect on the external flow
  ➢ Large-scale coherent flow structures (spanwise vortices) are formed by localized residual heating, via inviscid instability
  ➢ Significant flow control authority in subsonic flows (up to $M = 0.3$), scalable to large dimensions ($\sim 1$ m)
Summary (cont.)

• Flow control by accelerated vibrational relaxation:
  - Injection of “relaxer” species in nonequilibrium flow
  - Temperature and pressure rise due to accelerated relaxation
  - Strong effect on supersonic shear layer

• Outstanding issues:
  - Can “late” small-scale random perturbations be used for boundary layer flow tripping (e.g. see Yan and Gaitonde, Phys. Fluids 2010)?
  - Can accelerating vibrational relaxation (e.g. by CO₂ injection) enhance NS-DBD actuator flow control authority?
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