Honeycomb Discharge – Its Physical Properties and Chemical Potential for Environmental Applications

Karol Hensel*, Gokul Selvaraj, Richard Cimerman, Mario Janda

Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
*Corresponding Author e-mail: hensel2@uniba.sk

Plasma catalysis provides a beneficial combination of nonthermal plasma (NTP) with catalysis that has many potential environmental applications including air pollution control. Plasma catalytic reactors usually utilize dielectric barrier discharges packed with catalyst pellets, where discharge propagates in a contact with the pellet catalyst and maintains catalytic surface reactions. Another option for plasma catalytic reactor represents combination of NTP with honeycomb catalysts. From the perspective of effective surfaces involving chemical reactions, pellets have a structural disadvantage over honeycombs, as they provide high surface-to-volume ratio, low pressure drop and high mass and heat transfer. Generation of stable discharges in channels of the honeycomb represents a major challenge in honeycomb discharge from a practical perspective. In last two decades, honeycomb discharges have been studied both experimentally and theoretically [1]. In many studies glass capillary tubes were used for discharge visualization and emission spectroscopy. Numerical simulations helped to understand discharge generation, and propagation dynamics inside honeycomb monoliths and capillary tubes, and reported in the effects of tube radius, dielectric constant, gas humidity, etc. The chemical activity of the discharge was tested for O3 production, hydrocarbons removal and the regeneration of diesel particulates [2, 3].

This contribution summarizes our results on generation of discharges in capillary tubes and honeycomb monoliths. Electrical and optical measurements were performed in various geometry (diameter, length, cpi), gases (air, N2, O2, H2O) and power supplies (AC, DC, pulsed). The results showed dominant effect of tube diameter and humidity on discharge propagation velocity [4]. Tests with a bundle of capillary tubes were performed to assess the overall stability and spatial homogeneity of the discharge. The discharge was generated by a combination of DC an AC discharges in a pellet bed [4] or in a multi-hollow DBD [5]. The homogeneity and the stability largely depended on the discharge polarity, ballasting resistor, and gas humidity. At last, the discharges generated in honeycombs monoliths of various geometry (length, cpi) were tested. They were also briefly subjected to the investigations of its plasma chemical activity (generation of O3 and toluene removal).

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KEYWORDS: honeycomb discharge, capillary tubes, plasma catalysis, exhaust gas cleaning

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[4] K. Hensel, Eur. Phys. J. D 54 (2009) 141
[5] R. Cimerman et al. Int. J. Plasma Environ. Sci. Technol. 15 (2021) e01003

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Karol HENSEL, Gokul SELVARAJ,
Richard CIMERMAN, Mário JANDA, Zdenko MACHALA

Faculty of Mathematics, Physics and Informatics,
Comenius University, Bratislava, Slovakia
hensel@fmph.uniba.sk

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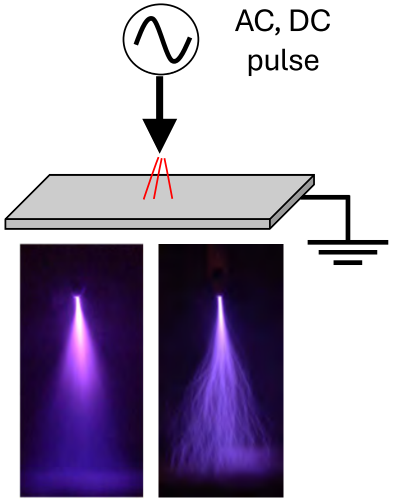
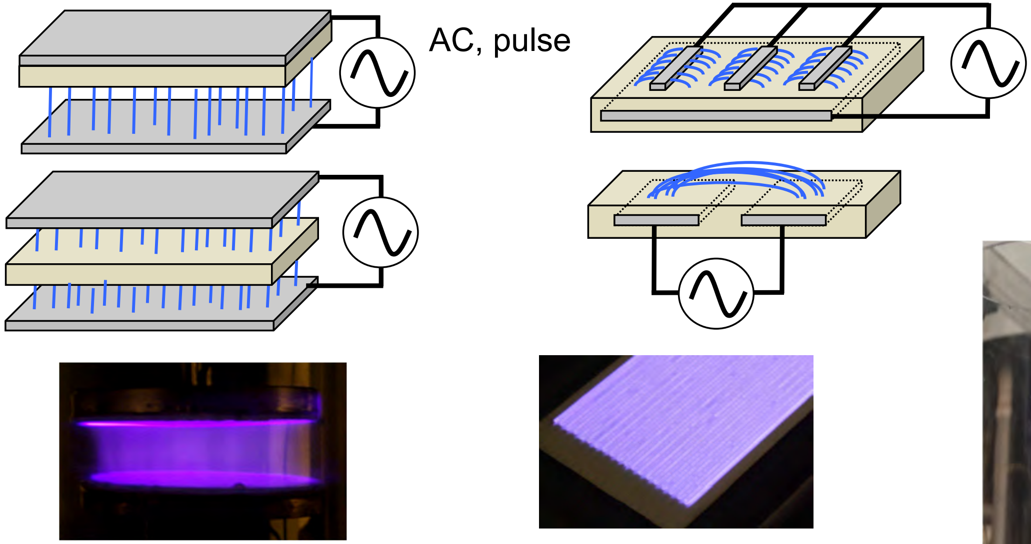
Atmospheric Discharges

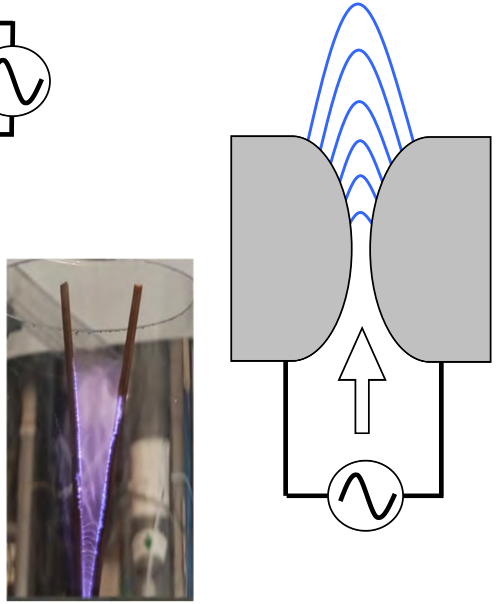
corona discharge



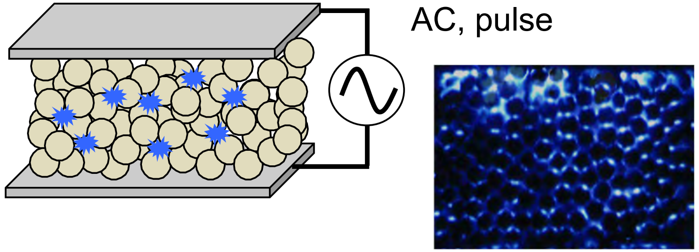
barrier discharges



gliding arc discharge



packed-bed discharge



plasma jet

electrodes
dielectrics
high gas flow

Applications of Plasma Discharges

- Environmental applications
  - ✓ air pollution control (exhaust gas treatment – VOC, NOx, CO_2, PM removal)
  - ✓ water cleaning (ozone generation)
- Biomedical and agricultural applications
  - ✓ volume and surface decontamination and sterilization …. therapy (cancer, ulcers)
  - ✓ seed germination, plants growth
  - ✓ food and package processing
- Energy applications
  - ✓ fuel (CH_4) reforming and H_2 generation (power-to-X)
  - ✓ plasma assisted combustion and ignition
- Material applications
  - ✓ plasma cleaning and etching
  - ✓ surface modification and activation
- Optical applications
  - ✓ light sources
  - ✓ plasma displays
  - ✓ gas detectors

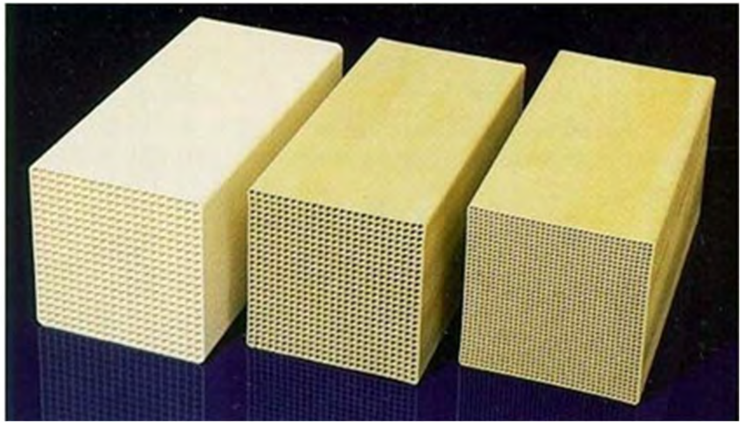
Pros/cons of plasma applications

+ high reactivity
+ efficient gas-phase reactions
- poor selectivity
- high power consumption
- formation of undesired products

Catalysts and … Combination with Plasma

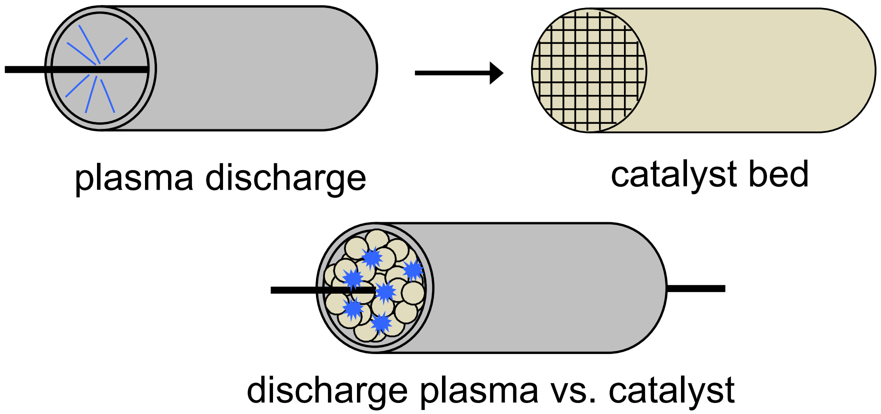
pellets
(size 1 – 5 mm)

foams
(porosity 10 μm – 1 mm)

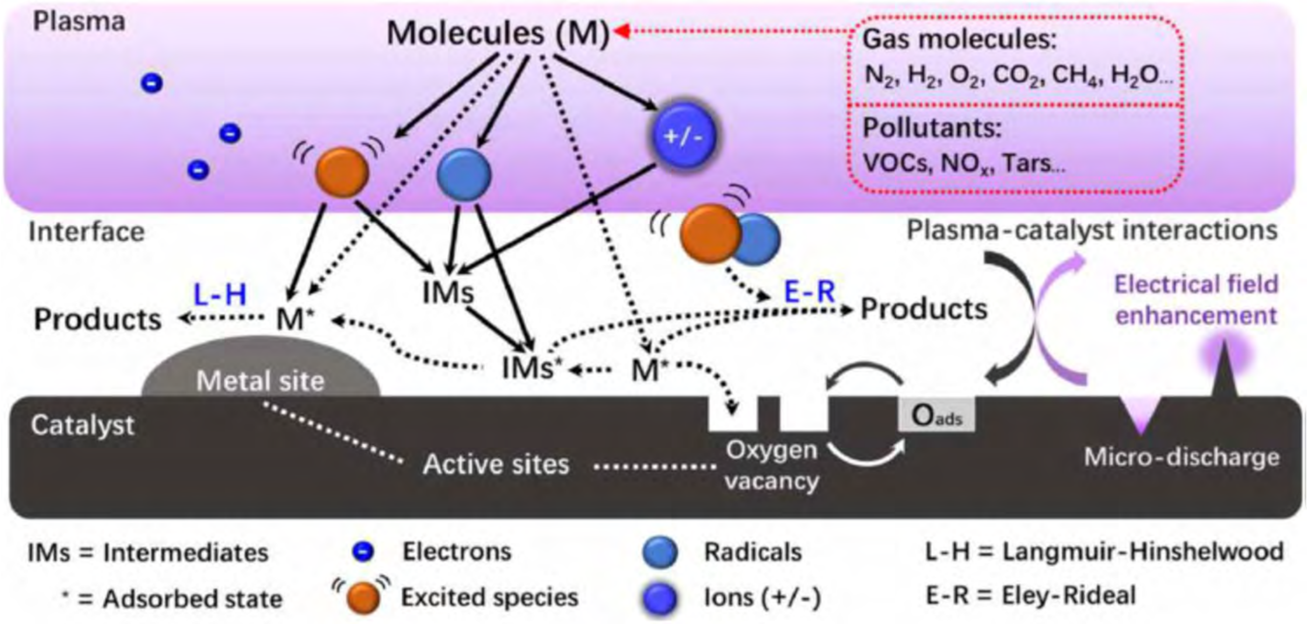


honeycomb monoliths
(diameter 10 μm – 1 mm, CPSI 50-400)

Pros/cons of catalysis
+ high reaction rate
+ high selectivity
+ efficient surface reactions
- high activation temperature
- demand for noble metals
- limited lifetime



Plasma Catalysis



A. Bogaerts, X. Tu, J. C. Whitehead, et al.
J. Phys. D: Appl. Phys. **53** (2020)

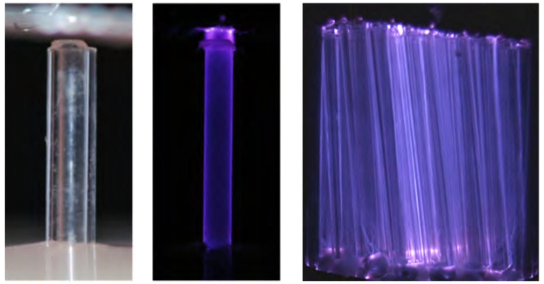
- Their interaction affects the chemical process (removal efficiency, selectivity, carbon balance).
- Catalyst effect on discharge → change of electric field; discharge mode and distribution; adsorption of pollutants.
- Discharge effect on catalyst → UV activation; reaction of species with surface; plasma induced desorption; change of catalyst dispersion.

Pros/cons of plasma catalysis
+ higher reaction rate
+ high selectivity and good carbon balance
+ possible synergy
+ low yield of undesired by-products
… but not always ideal

Overview of Presented Results

- How a material (structure, dimensions, catalytic properties) affects the discharge ignition, propagation and chemical activity?
- Catalytic **pellets** vs. **honeycomb** → surface-to-volume ratio, pressure drop, mass and heat transfer.
- Summary of results on generation of discharges in glass capillary tubes and ceramic honeycomb monolith.

discharge in capillary tubes

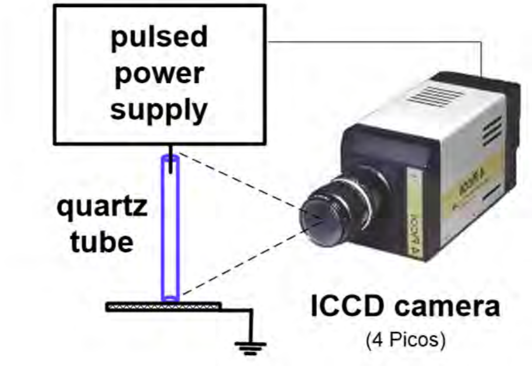


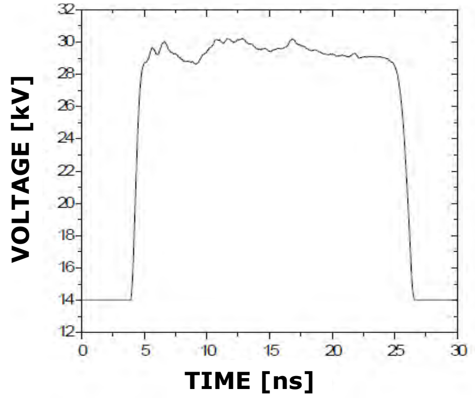
discharge in honeycomb monoliths

- **Materials** of various geometry (diameter, length, CPSI), various **power supplies** (AC, DC, pulsed).
- **Electrical diagnostics** included I/V measurements and power evaluation.
- **Optical diagnostics** included photography, emission spectroscopy and fast camera imaging.
- **Chemical activity** was briefly investigated by monitoring O_3 production in bundle of tubes and honeycomb monoliths.

R. Cimerman, et al, *Phys. Plasmas 29,* 113510 (2022)
H.-H. Kim, et al. *Int. J. Plasma Environ. Sci. Technol. 15,* e01004 (2021)
R. Cimerman, et al. *Int. J. Plasma Environ. Sci. Technol. 15,* e01003 (2021)
K. Hensel, *Eur. Phys. J. D* 54, 141 (2009)
K. Hensel, et al. *IEEE Trans. Plasma Sci.* 36, 1282 (2008)
G. Selvaraj et al. *CESPC-10*, Bucharest (2025)

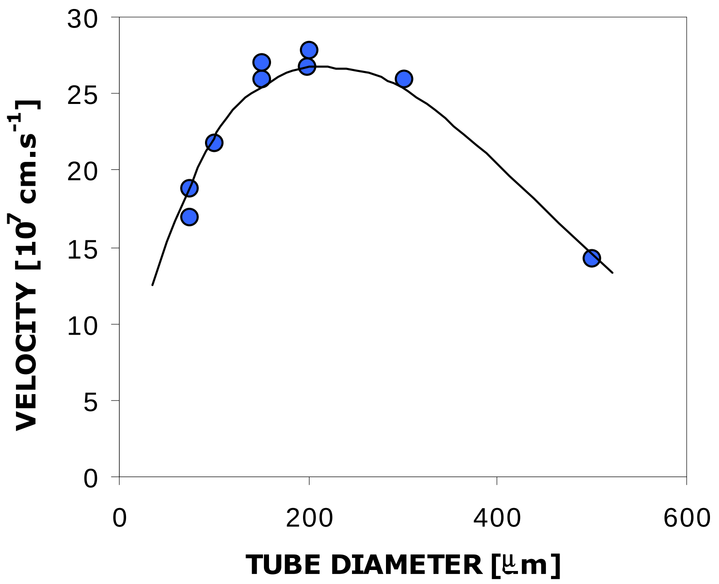
Discharge in Single Tube – Pulsed HV





Tubes → dimensions: Ø 50 µm – 2 mm
Electrode → dimensions (material): Ø 50 µm
Pulse → amplitude 7-30 kV, duration 20 ns
Gas → ambient air

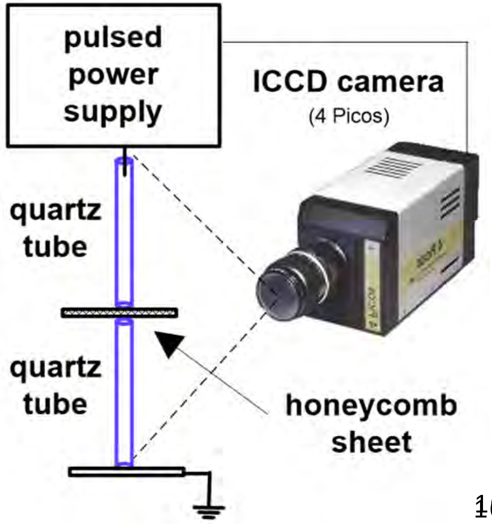
- Tube diameter affects both the structure and the velocity of the discharge.
- Structure: tubular vs. homogeneous.

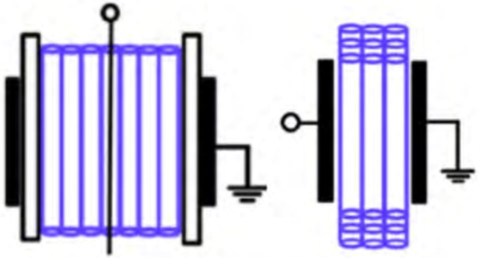


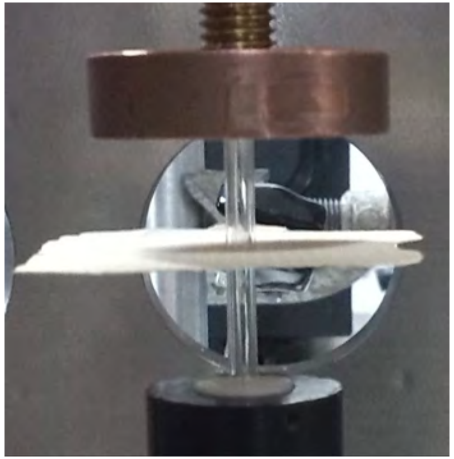
Discharge propagation velocity *vs.* tube diameter

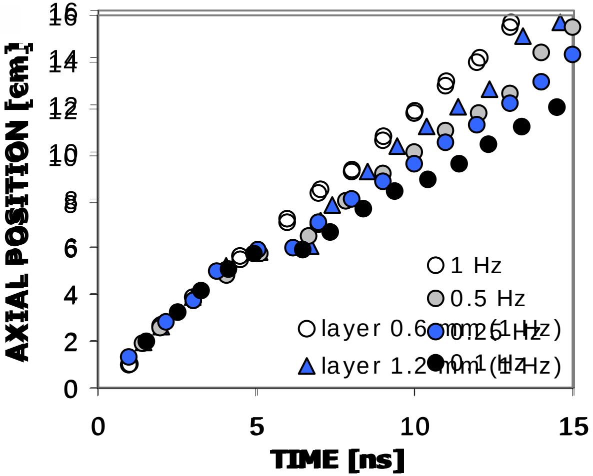
- Propagation velocity linearly ↑ with amplitude of applied voltage ↑.

Discharge in Single Tube + Sheet – Pulsed HV

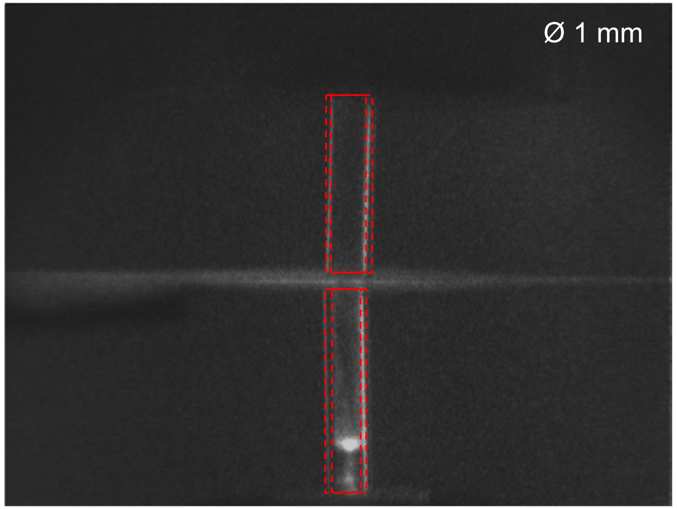


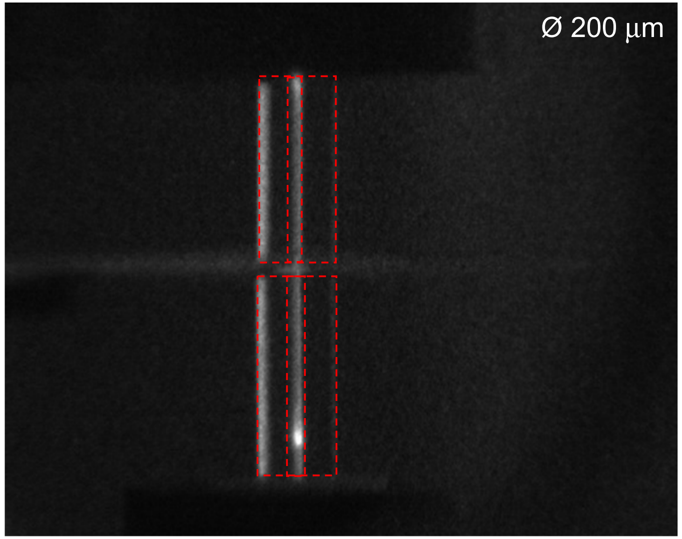




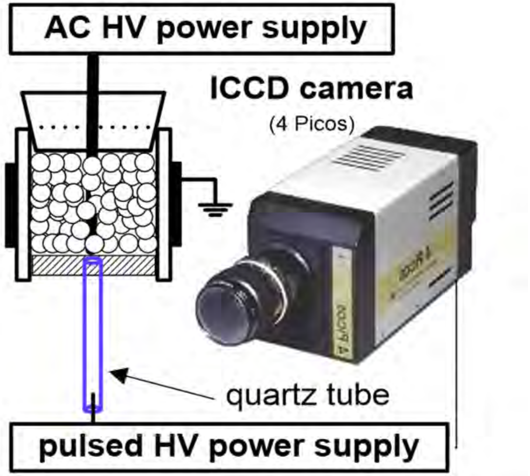


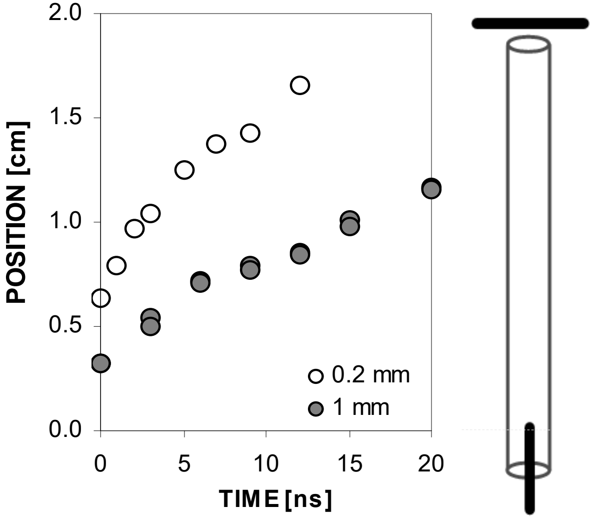
Discharge propagation velocity

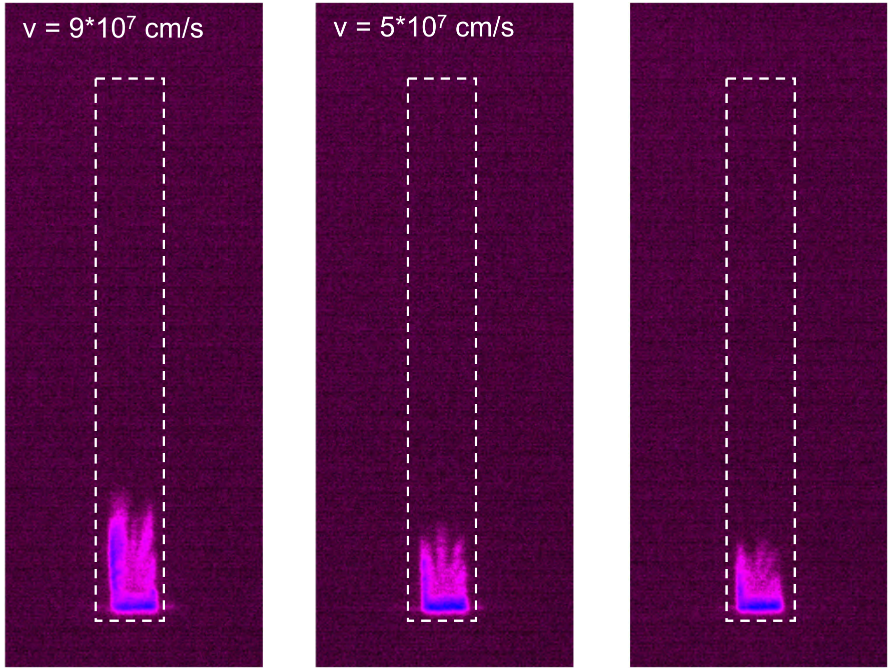




Discharge in Single Tube – Pulsed HV + AC HV





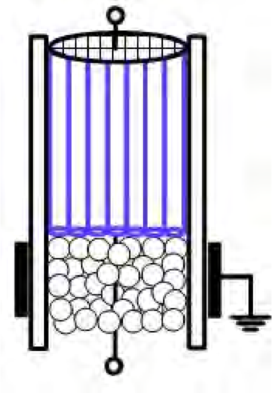


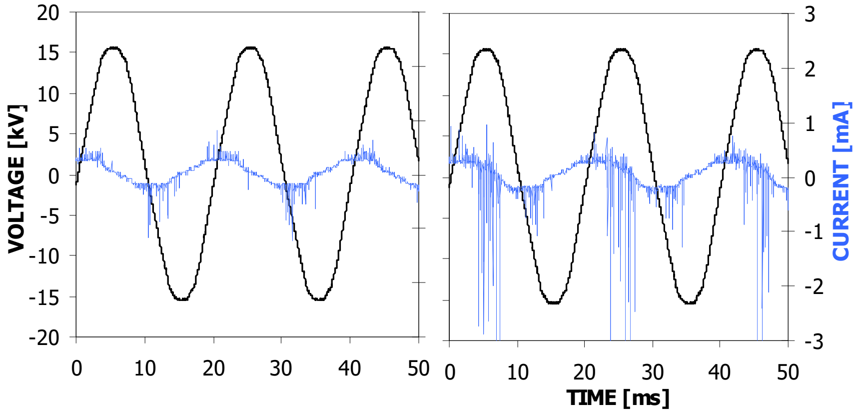
U_{AC}= -13 kV U_{AC}= 0 kV U_{AC}= +13 kV

Discharge propagation toward cathode
vs. time *vs.* AC applied voltage
[∅ = 1 mm, L = 3 cm, U_{puls} = +15 kV, Δt_{puls} = 20 ns]

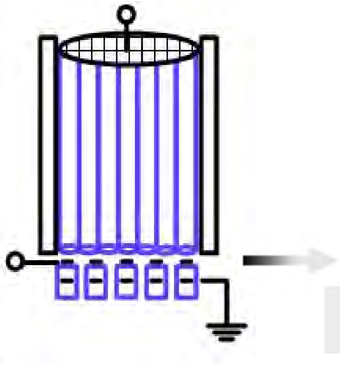
Discharge in Bundle of Tubes – DC + AC HV

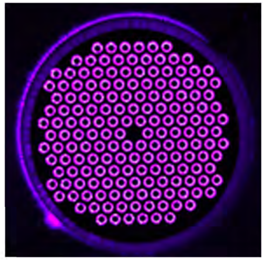
Discharge assisted by AC **pellet bed discharge**



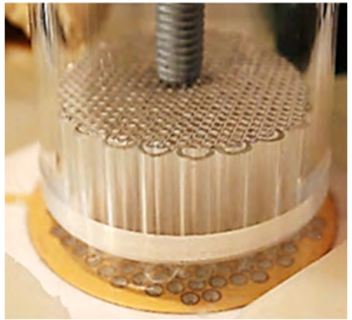


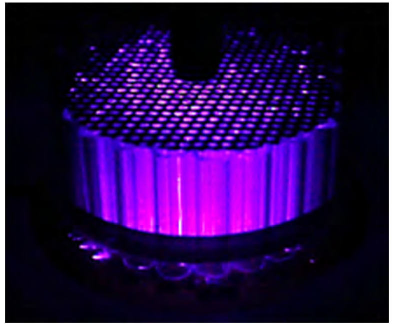
Discharge assisted by AC **multi-hollow DBD discharge**





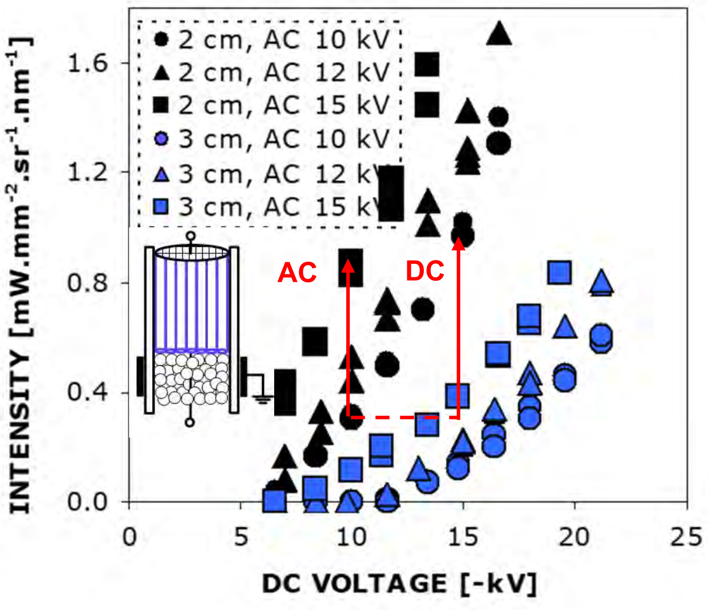
multi-hollow DBD



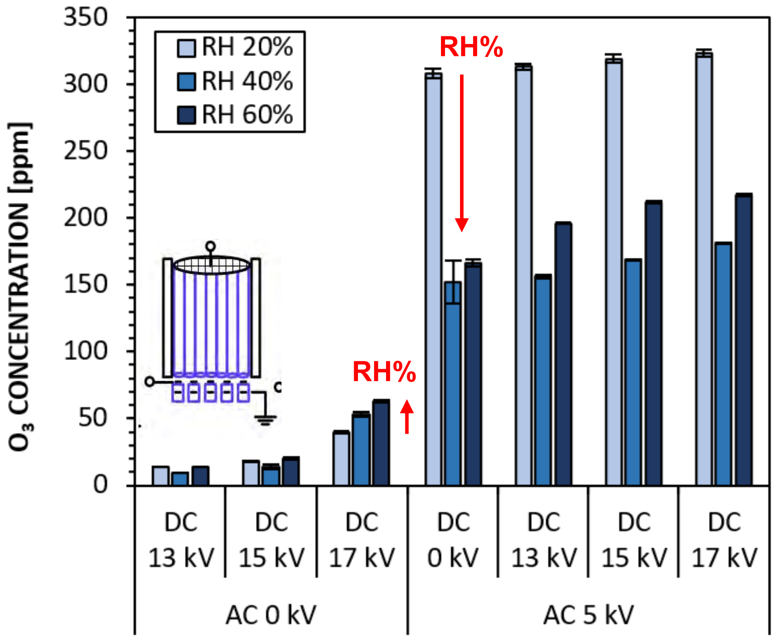


- The auxiliary AC discharge served as ionizer, while DC bias extended the discharges inside the tubes.

Discharge in Bundle of Tubes – DC + AC HV



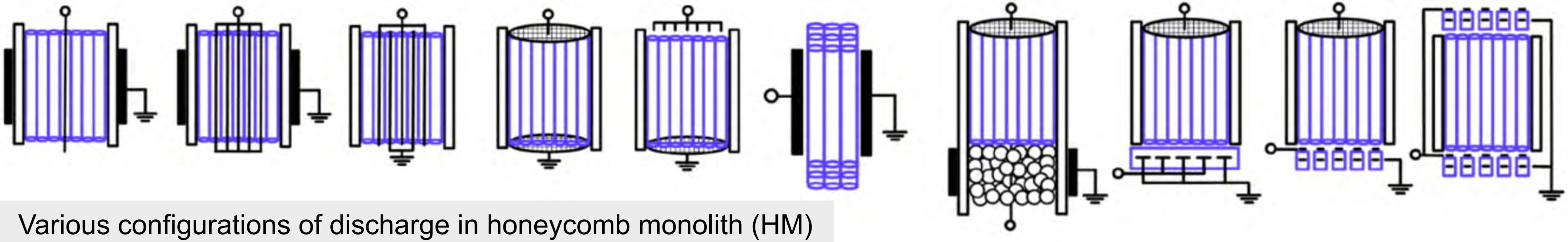
Emission intensity vs. DC and AC voltages *vs.* tube length (L) [**pellet bed**, Ø 2 mm]



O_3 production vs. DC and AC voltages *vs.* RH% [**micro-hollow SDBD**, Ø 2 mm]

- The homogeneity, stability as chemical activity of the discharges strongly depended on the applied voltages (U_{AC}, U_{DC}), and feed gas humidity (RH%).

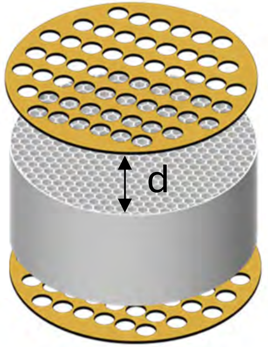
Discharge in Honeycomb Monolith (HM)



Various configurations of discharge in honeycomb monolith (HM)

H.-H. Kim, et al. *Int. J. Plasma Environ. Sci. Technol.* **15**, e01004 (2021)

Author	Catalyst	Flowrate (l/min)	Humidity (%)	Power (W)	Pollutant	C (ppm)	eff (%)
V. T. Nguyen, Chem. Eng. Sci. 2023	Pd:Mn/Al2O3/HM	5	3	-	methyl ethyl ketone	500	87
S. Saud, Chem. Eng. J 2023	PdO/ZSM-5/HM	60	3.1	10-35	ethylene	30	96
V. T. Nguyen, Chem. Eng. J. 2022	Pd/Al2O3/HM	30-70	1.5-2.7	30-90	isopropanol	300	94
M. M. Hossain, Chem. Eng. Research Design 2022	H-ZSM-5/HM	60	3	84	toluene	15	85
M. M. Hossain, Appl. Catal. A. Gen. 2022	Co/ZSM-5/HM	20	90	18	ethylene	20-40	85
S Saud, J. Hazard. Material. 2022	Pd/ZSM-5/HM	5-40	3	2-8	ethylene	5	97
V. T. Nguyen, Appl. Catal. B. Environ. 2022	Pd/Al2O3//HM	-	1.5	-	ethyl acetate	30	93
V. T. Nguyen, J. Hazard Mater. 2021	Pd/Al2O3/HM	-	3	-	ethyl acetate	-	96
M. M. Hossain, J. Hazard Mater. 2021	Co:Pd:Pt:La/HM	60	2.9	58	toluene	15	80
M. M. Hossain, J. Envion. Chem. Engineer, 2021	Co,Pd,La/ZSM-5/HM	10	3	-	styrene	-	100
D. B. Nguyen, Environ. Sci. Technol. 2021	Co:Pd:Pt:La/HM	60	1.2-2	40	nitrogen oxides	100	29
N. Matyakubov, J. Hazard Mater. 2021	Co:Pd:Pt:La/HM	60	3.3	-	acetaldehyde	5	67
S. Saud, J. Hazard Mater. 2021	Pd/ZSM-5/HM	70	3	-	-		-
D. B. Nguyen, Plasma Source Sci. Technol. 2021	HM	60	1.5-3	-	-		-
D B Nguyen, Chem. Eng. J. 2020	HM	75	2	30	-		-



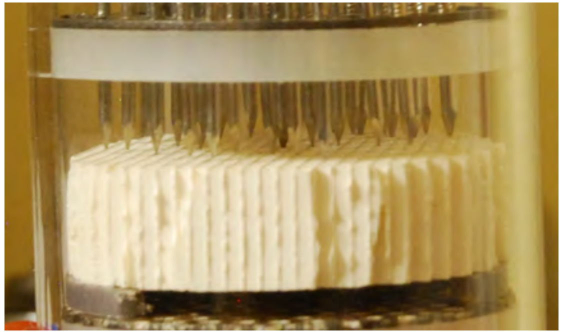
Young Sun Mok group work
Jeju National University, Korea

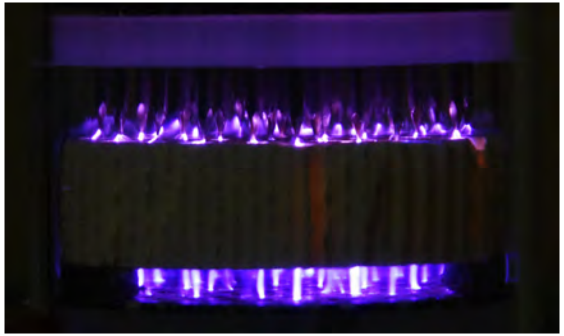
Discharge in honeycomb monolith
[L = 50 mm, D = 93 mm, CPSI = 300, d = 2 mm, f = 400 Hz, U_{AC} = 15-20 kV]

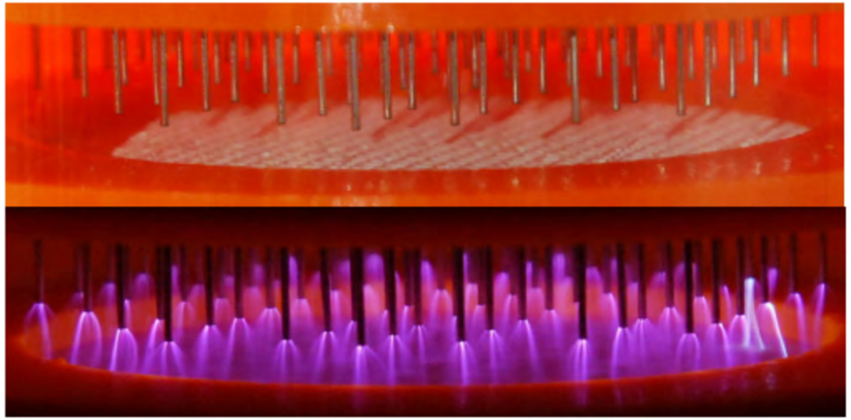
CPSI = cells per squared inch
d = gap (distance) between HV electrode and HM

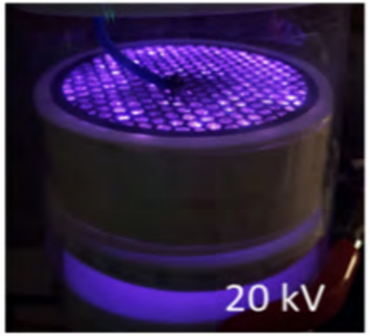
Discharge in Honeycomb Monolith – Photos

- We investigated the effects of … type and amplitude of applied voltage U_{DC}, U_{AC}, gap d (0-5 mm) flow rate Q (0.5-2 L/min), humidity RH (50-90%), CPSI (64-300), HM thickness L (single, double),



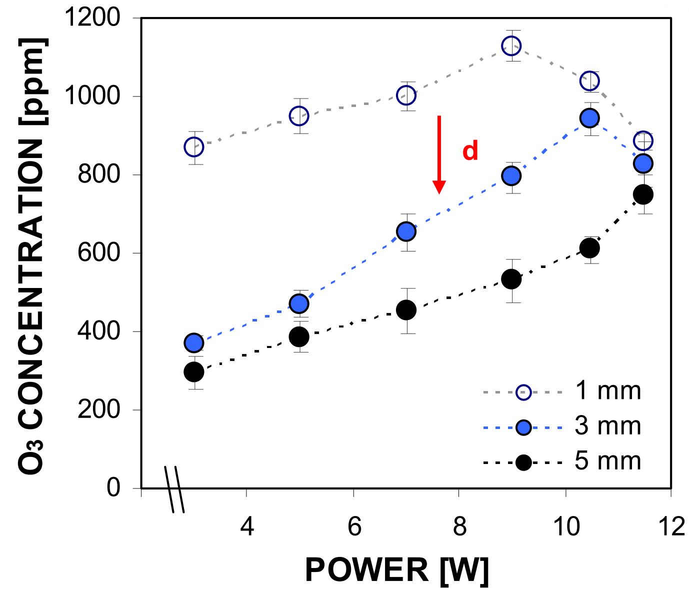




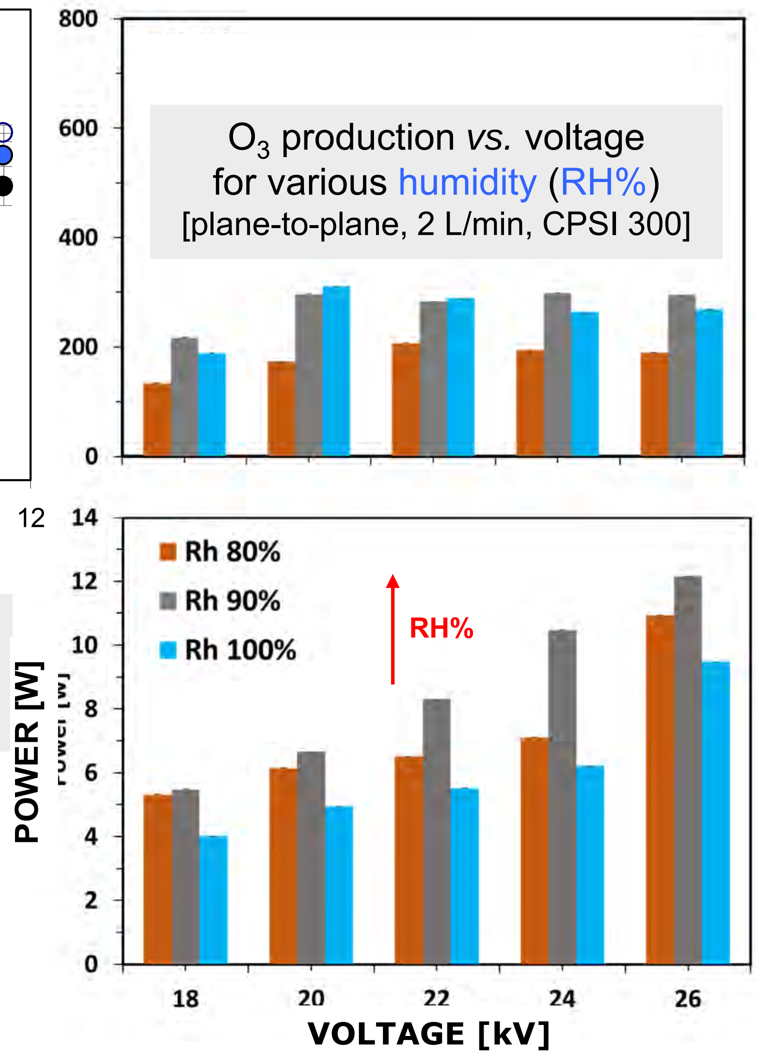


G. Selvaraj et al., *CESPC-10,* Bucharest (Romania), Sept 1-5 (2025)

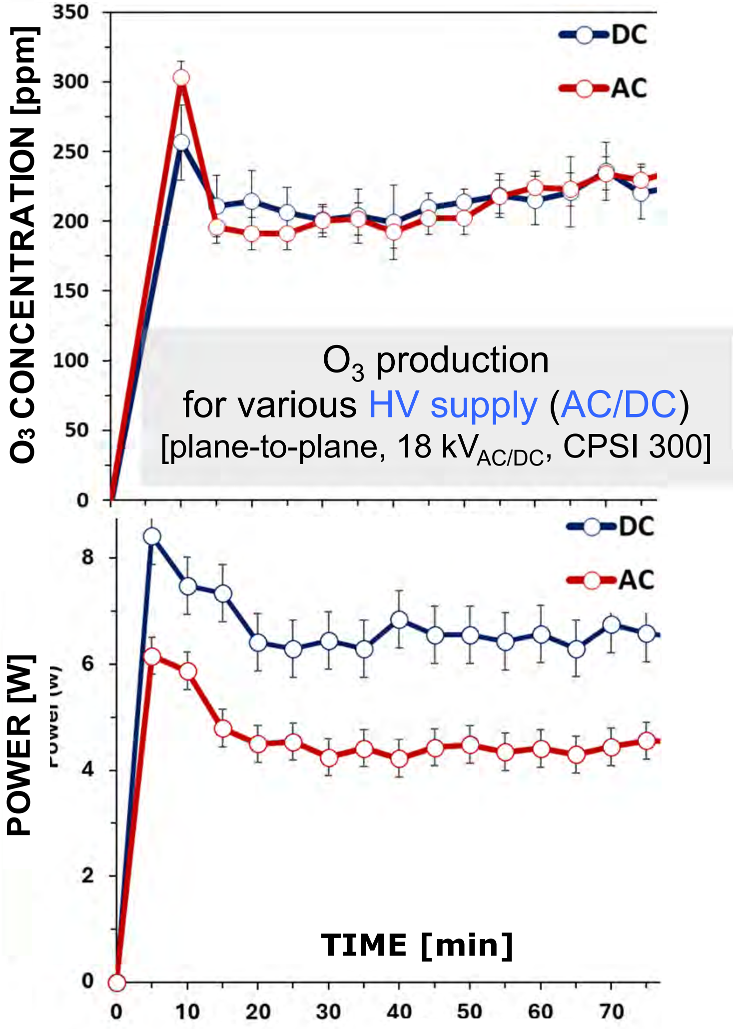
Discharge in Honeycomb Monolith – Effects



O_3 production *vs.* discharge power
for various pin-to-honeycomb gap (d)
[pins-to-plane, 0.25 L/min, CSPI 200]

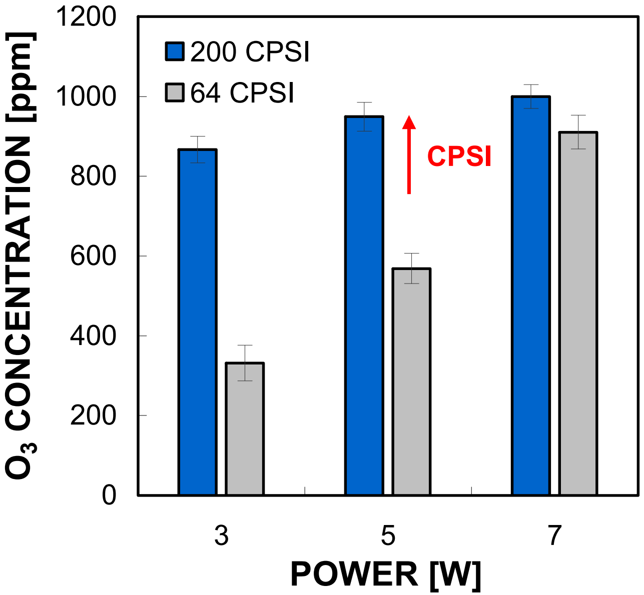


O_3 production *vs.* voltage
for various humidity (RH%)
[plane-to-plane, 2 L/min, CPSI 300]

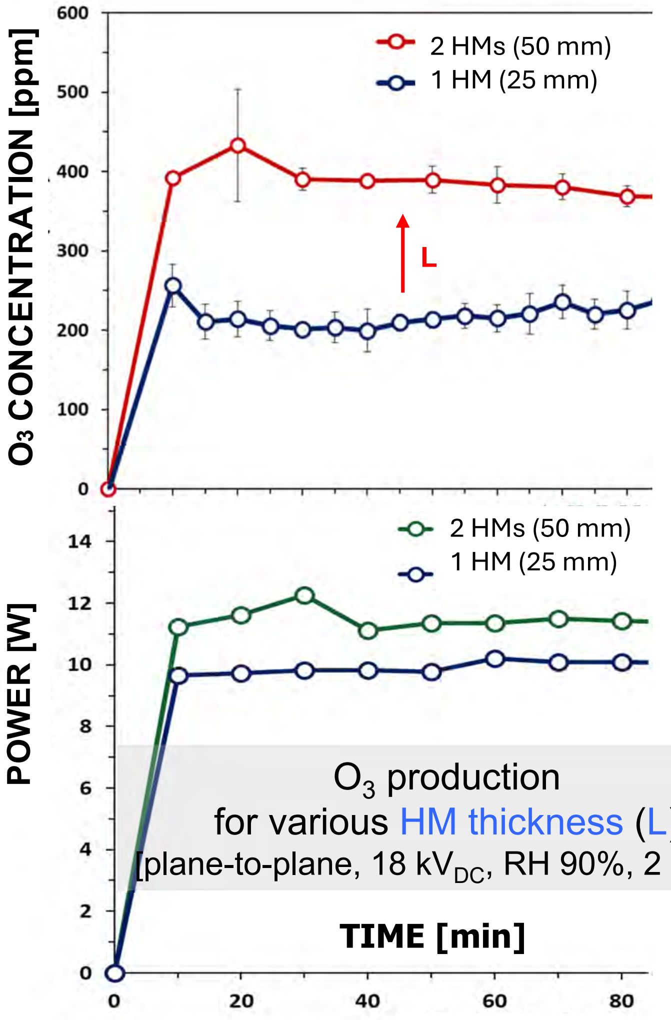


O_3 production
for various HV supply (AC/DC)
[plane-to-plane, 18 $kV_{AC/DC}$, CPSI 300]

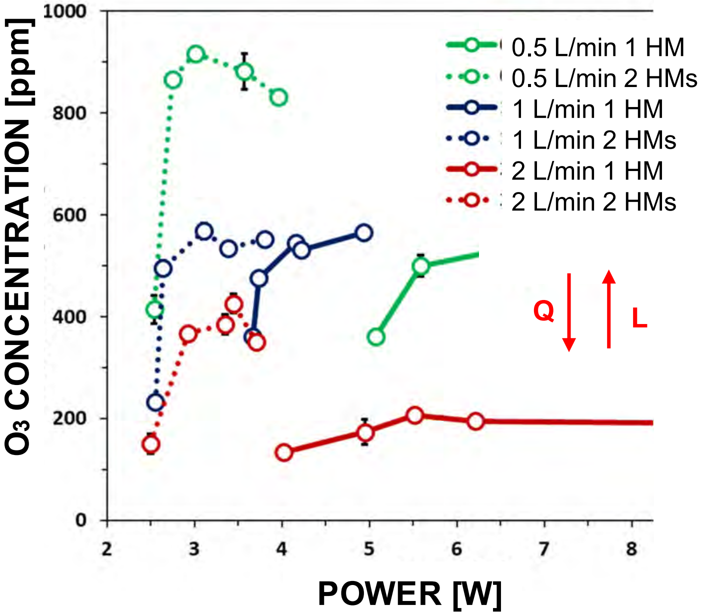
Discharge in Honeycomb Monolith – Effects



O_3 production *vs.* discharge power for various CPSI
[pins-to-plane, 0.25 L/min, d = 1 mm]



O_3 production for various HM thickness (L)
[plane-to-plane, 18 kV_{DC}, RH 90%, 2 L/min]



O_3 production *vs.* discharge power for various flow rate (Q) and HM thickness (L)
[plane-to-plane, U_{DC}, RH 90%]

Summary

- Atmospheric **discharges in contact with materials** (dielectric/catalytic) are important for many plasma applications (air pollution control, fuel reforming, surface treatment and modifications).
- Understanding **plasma–catalyst interaction** is important for process optimization.
- We investigated discharges in capillary tubes and honeycomb monolith generated by various power supplies and their combination.
- Effects of **tube diameter** (Ø), **discharge gap** (d), **type of voltage** (U_{DC}, U_{AC}), **humidity** (RH%), **CPSI** on discharge properties and chemical activity were briefly presented.

- Discharge propagation velocity in tubes was of ~ 10^7-10^8 cm/s and it ↑, for tube diameter ↓.
- Discharge in tubes can be maintained by auxiliary discharge → effectively enhanced/suppressed by AC bias.
- Ozone production ↑ for discharge power (P) ↑ and CPSI ↑
  for electrode-to-HM gap (d) ↓, gas flow rate (Q) ↓ …. humidity (RH) ↑↓.

- There are still issues to be resolved and improved,
  e.g. total volume of plasma, generation in every channel, stability, discharge mode.
- Discharges in honeycomb (confined geometries) show a promising potential and these results may serve as a good starting point for future investigations.