Experimental Study of Secondary Electron Emission and its Role in Atmospheric Electricity

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I. Summary

Paschen's law underlies our understand of scaling properties of electric discharges. It describes non-thermal, self-sustained discharges occurring in high voltage, low current, and low-pressure conditions between two parallel plate electrodes (Raizer et al., 1991). Originally established experimentally for various gas mixtures, Townsend (1915) developed a formal theory that relies on an exponential fit of the primary ionization coefficient $\alpha_{\text{eff}} \approx Ap\exp(-Bp/E)$ and the poorly understood secondary electron emission (γ). Raizer et al. (1991 p.75) states that "The data on γ are incomplete and often contradictory." The commonly used A, B, γ constants do not traditionally consider electrodes' geometries and materials. Riousset et al. (2022) proposed a new formalism suitable for non-planar geometries using the reduced effective ionization coefficient α_{eff}/p and mobility μp. The new model accounts for volume and drift velocity changes along the avalanche path via a power law approximation of μp. We propose to use this new formalism and explicitly characterize the constants A and B in the effective ionization α_{eff}. In addition, we develop an experimental setup for their validation. The discharges are produced in Embry-Riddle Aeronautical University's Lightning Plasma Chamber (LPC). The initiation voltage (V_{cr}) is measured at specific pressures p and distances d in air. Distances and pressure can be adjusted using a linear feedthrough (LFT) and mass flow controller (MFC), respectively. In addition, we seek to establish how γ depends on the nature of the electrode, its geometry, surface condition, and the gas of the environment. We show that the v. Engel-Steenbeck equation (Fridman & Kennedy, 2004) and the assumed value of γ does not adequately characterize the critical voltage under non-planar geometries. We propose a χ^2−analysis to assess the dependencies of γ on the environmental parameters and obtain accurate values for A and B. These variations may prove especially important for the initiation of Transient Luminous Events occurring near the ionosphere at low pressures.

II. Introduction

Paschen's Law & Townsend Theory

- $V \geq V_{cr}$ ⇒ **Collision e-N (N: neutral gas) ⇒ Ionization of neutrals ⇒ 1 ion / 2 free electrons ⇒ Avalanche** (Townsend, 1915).
- Secondary Electron Emission S.E.E. (γ)
  - **Experimental.**
  - **Depends on** metallicity, pressure, distance, geometry, and gas mixture (Ellion, 1965).

Paschen's Law: State of the Art

- Main formalism for Townsend's theory.
- Model of infinite parallel plates.
- Not applicable to non-uniform geometries.
- Left of minimum is ill-defined (Knaster et al., 2012).
- A and B coefficients are defined by Stoletov point.

Objectives

- Definition of a new system of equations accounting for (1) distance between cathode and anode (2) S.E.E. (γ).
- Comparison with experimental data collected in the LPC chamber.
- A and B coefficients defined based on LSQ fit of either:
  - Plot of E/N vs α_{eff}
  - Plot of pd vs. V_{cr} = Bpd/ln(Apd − ln(1/ γ +1))
- Estimates of S.E.E. (γ) using theory.

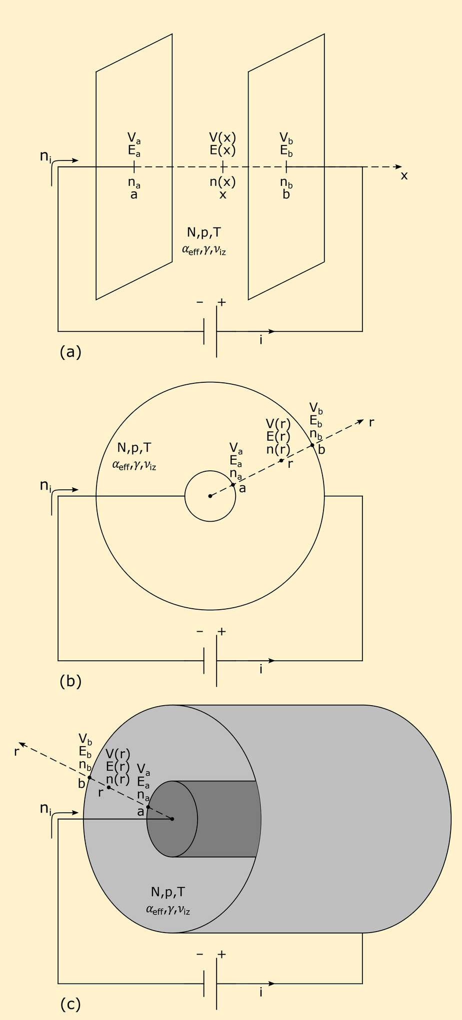

Figure 1. Geometries:
(a) Parallel plates;
(b) Coaxial cylinders;
(c) Concentric spheres.

III. Methods & Models

a) Experimental setup

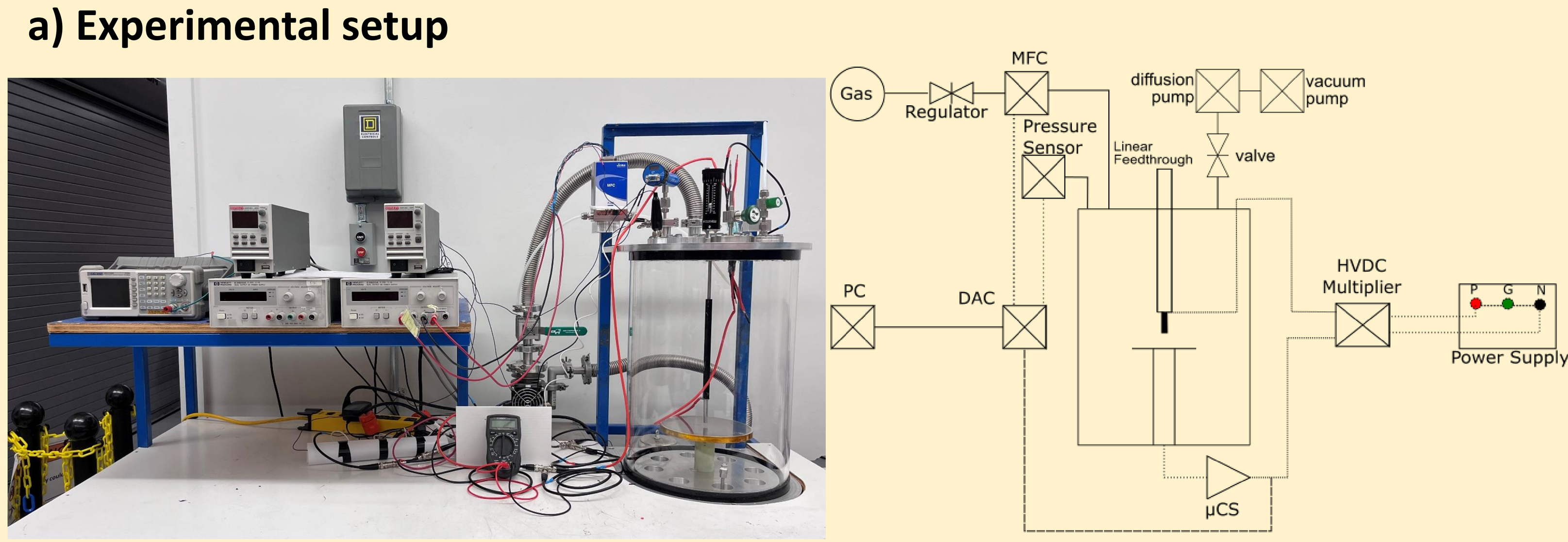

Figure 2. Experimental setup for initiating electrical dischargers in various environments. HVDC multiplied input voltage amplifies 0-25V to 10-3000V. Left: Experimental setup. Right: Schematic of the experiment.

III. Methods & Models (cont.)

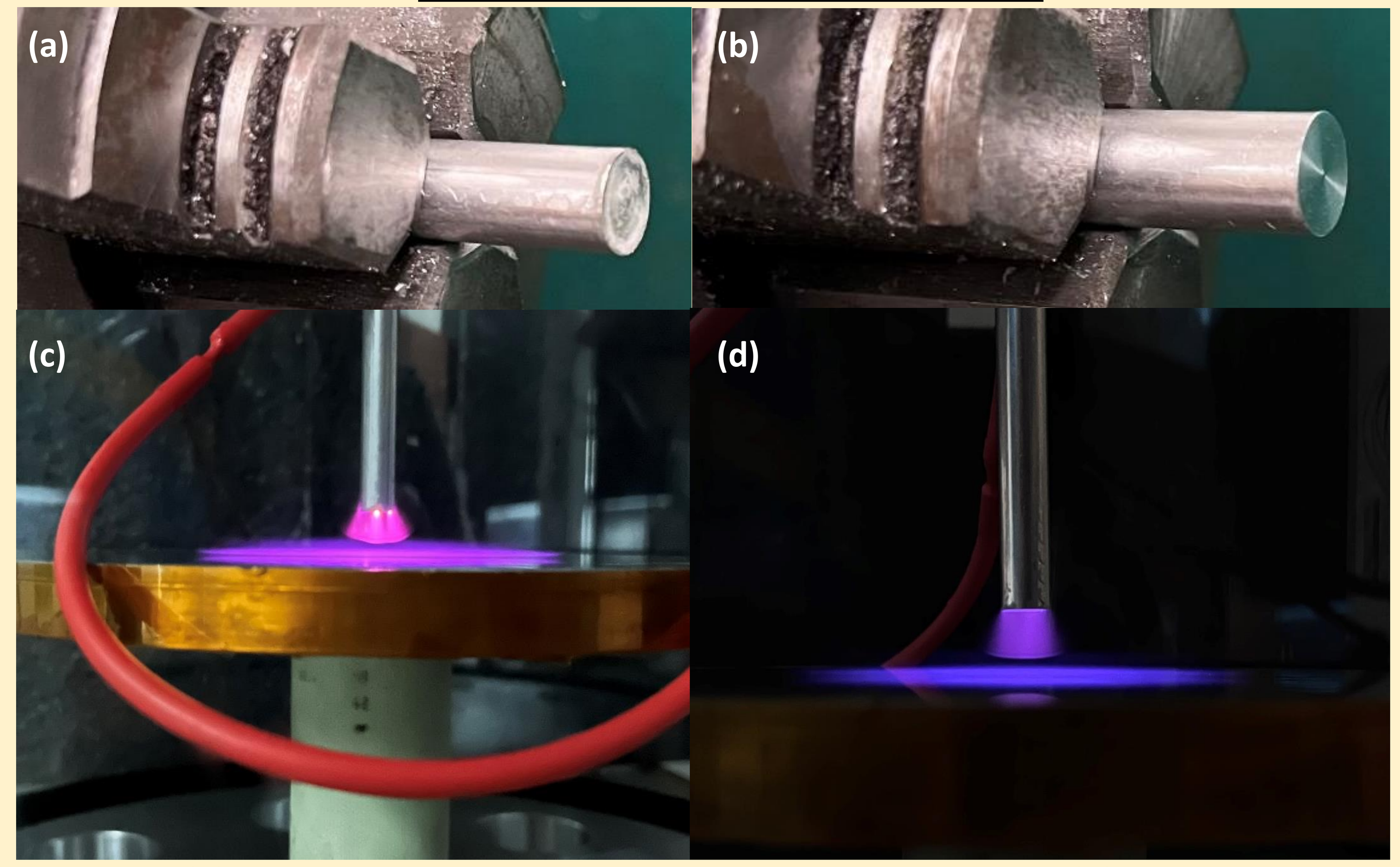

Figure 3. (a) Rough surface electrode from previous discharges; **(b)** Smooth surface electrode; **(c)** Glow discharge from rough surface, γ=0.0029; **(d)** Glow discharge from smooth electrode, γ=0.0049.

b) Theory

- Plasma relationships:

$$\nabla\cdot\vec{E}=0 \quad (1)$$

$$v_{iz}=\alpha\, v_d \text{ where } \frac{\alpha}{N}=Ae^{-\frac{B}{E/N}} \quad (2)$$

$$v_d=\mu E \text{ where } \mu N=C\left(\frac{E}{N}\right)^D \quad (3)$$

$$\frac{\partial n}{\partial t}+\nabla\cdot(n\,\vec{v}_d)=v_{iz}\,n \quad (4)$$

- Constitutive relationships between charge densities at a and b from primary secondary ionization and electronic currents:

$$n_a=n_\gamma+n_i \quad (5)$$

$$n_\gamma=\gamma(n_b-n_a) \quad (6)$$

$$n_b=A_v n_a \quad (7)$$

- Gauss' law $\nabla\cdot\vec{E}=0$ ⇒ E(r)/N
- Breakdown equation ⇒ $\frac{E}{N}\Big|_a$

$$\int_a^b\left(AN\exp\left(-\frac{B}{\frac{E}{N}\Big|_a}\left(\frac{r}{a}\right)^{\delta}\right)+\frac{D\delta}{r}\right)dr=\log\left(1+\frac{1}{\gamma}\right) \quad (8)$$

$\delta=0$: Cartesian ⇒ v. Engel–Steenbeck

$\delta=1$: Cylindrical

$\delta=2$: Spherical

- $\vec{E}=-\nabla V(r)\Rightarrow V_{\text{cr}}$

IV. Results

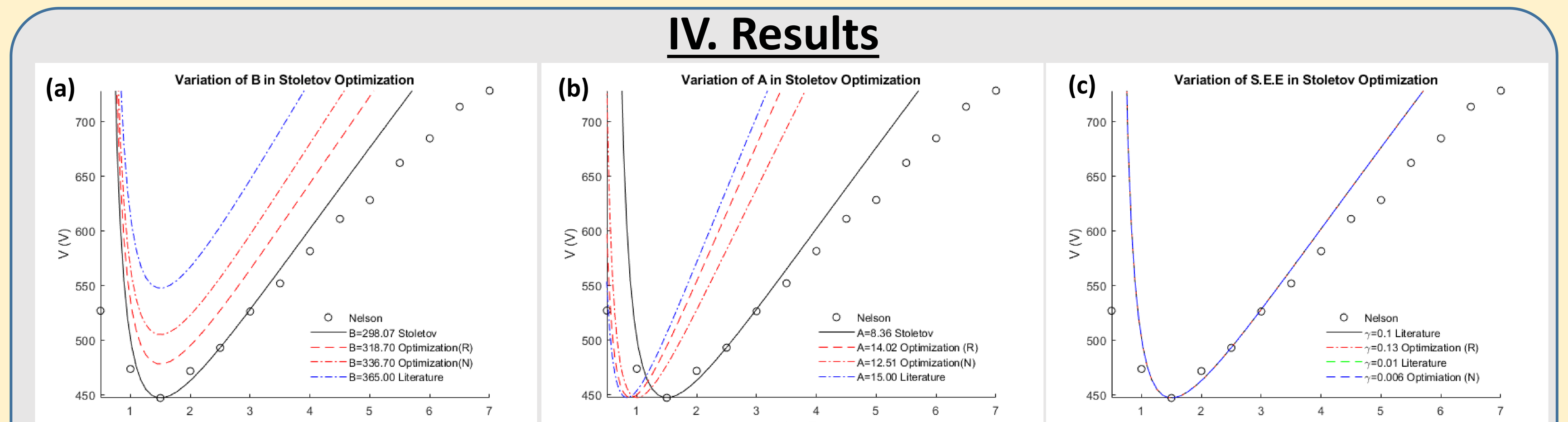

Figure 4. (a) Role of variable B in Paschen curves; **(b)** Role of variable A in Paschen curves; **(c)** Role of γ in Paschen curves. $B=V_{\min}/pd_{\min}$ $A=\bar{e}\ln\left(\frac{1}{\gamma}+1\right)/pd_{\min}$ (Fridman & Kennedy, 2004, p.210).

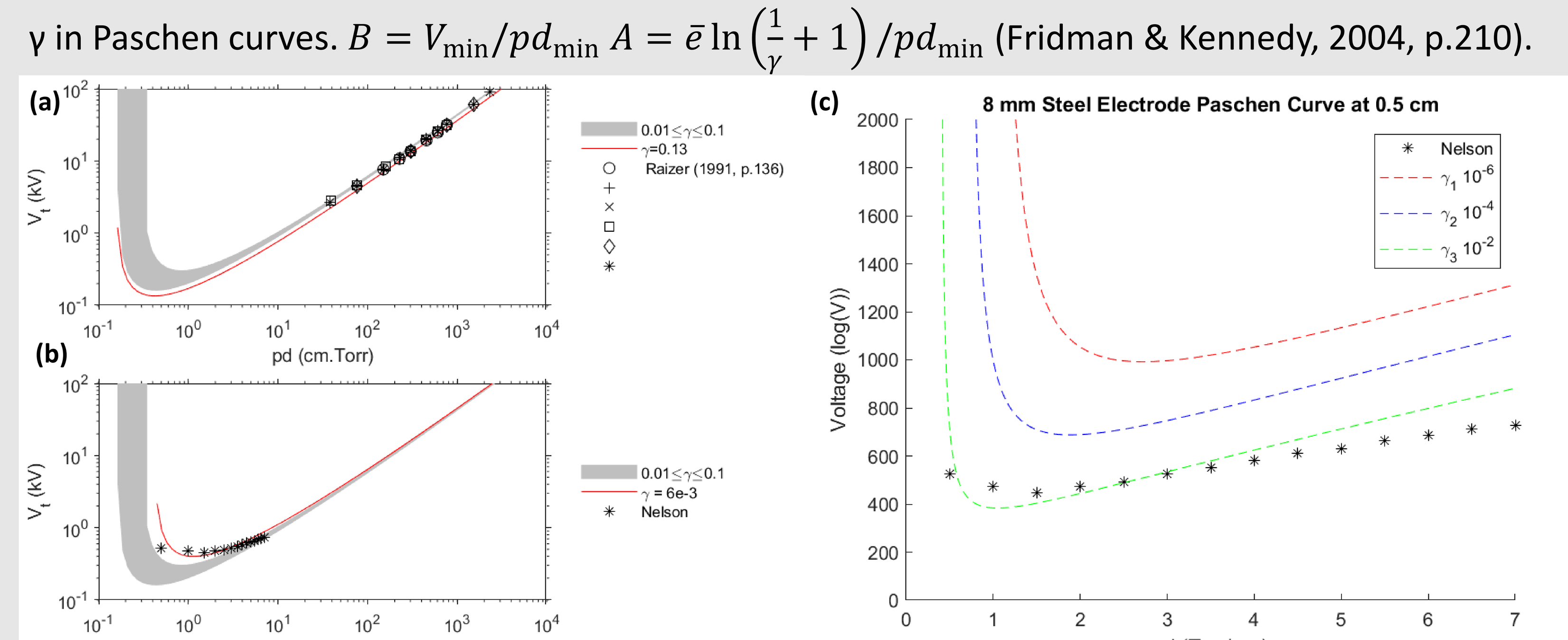

Figure 5. (a) Comparison of 'acceptable range' for Raizer et al. (1991) data; **(b)** Comparison of 'acceptable range' for Nelson data; **(c)** Discrepancy of Paschen curves in air from v. Engel-Steenbeck equation.

IV. Results (cont.)

	Case	Fixed Param.	Derived Param.	Tests	Optimization
Plates	1	A,B,γ	–	$\chi^2=11.40$	Baseline
	2	A,B	$\gamma=.13$	$\chi^2=1.19$	Paschen
	3	γ	$A=14.02, B=318.70$	$\chi^2=1.72$	Paschen
Cylinders	4	A,B,γ		$\chi^2=0.23$	Baseline
	5	A,B	$\gamma=0.005$	$\chi^2=0.13$	Paschen
	6	γ	$A=12.51, B=353.60$	$\chi^2=0.11$	Paschen
Point to Plane	7	A,B,γ	-	$\chi^2=879.56$	Baseline
	8	A,B	$\gamma=0.003$	$\chi^2=302.91$	Paschen
	9	γ	$A=12.80, B=420.20$	$\chi^2=107.12$	Paschen

Table 1. Case studies for air. Raizer et al. (1991, Tab.4.1) suggests that A = 15/(cm*Torr), B=365 V/(cm*Torr), γ = 10^{-2}. All optimizations based on best fit equation.

V. Discussion

Role of previous ionization path:

- Unpurged chamber ⇒ Presence of free ions/electrons ⇒ Easier breakdown ⇒ Lower V_{cr}.
- Purged chamber ⇒ Little/no free charges ⇒ Stricter conditions ⇒ Higher V_{cr}.
- Improper grounding ⇒ Easier breakdown ⇒ Lower V_{cr}.

Roles of primary α_{eff} and secondary electron emission γ:

- Discrepancy between experiments and theory when A, B calculated from Stoletov's points.
- Impossible to calculate A & γ separately based on v. Engel-Steenbeck equation ⇒ Discrepancies when LSQ fit is used.
- Surface conditions of electrode ⇒ accrued errors in discharge parameters.

VI. Conclusions

The principal results and contributions from this work can be summarized as follows:

- We developed a new experimental setup to create self-sustained electrical discharges in air.
- We preformed the first tests of scalability for the newly revised formalism for Paschen's law (Riousset et al., 2022, under review).
- We found discrepancies between theoretical calculations of critical voltage and experiments.
- We compared the estimates of A and B obtained from Stoletov's point to a LSQ fit and showed that the accepted gas constants and secondary electron emission only hold true at minimum critical voltage.
- We demonstrated that adopting the v. Engel-Steenbeck equation as a standard description of the Paschen curves does NOT let us calculate A and γ separately.
- We experimentally showed that rough surface conditions of electrode decreases the secondary electron emission.

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Acknowledgments

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