Electric discharges in air and CO_2 in non-planar geometries

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Abstract

At the basis of our understanding of dielectric breakdown, i.e., gas discharges, is Townsend's theory. Its formulation as Paschen's law describes non-thermal, self-sustained discharges occurring in high voltage, low current, and low-pressure conditions between two parallel plate electrodes (Raizer et al., 1997). Paschen's law has been developed for various gas mixtures but does not traditionally consider electrodes' geometry and material. Here we propose to develop a new formalism for equations adapted to these constraints and an experimental setup for its validation. The discharges are produced in Florida Tech's micro-Terrestrial Atmosphere Discharge Simulator (μTADS) where the critical (initiation) voltage V_{cr} is measured at specific pressures p and distance d in air and CO_2 mixtures comparable to Earth and Mars atmospheres. We show that the Engel-Steenbeck equation (e.g., Fridman & Kennedy, 2004): $V_{cr} = \frac{B(pd)}{C+\ln(pd)}$ (where $C = \ln(A) - \ln\ln\left(\frac{1}{\gamma}+1\right)$, A and B are empirically determined coefficients for each gas mixture and γ is the secondary electron emission coefficient) does not adequately characterize the critical voltage of non-planar geometries. This work supports the validation of new proposed formalism and improvement of safety systems subject to potential discharges.

I. Introduction

Paschen's Law & Townsend Theory

- Townsend's theory ⇒ Breakdown from an electron avalanche b/w parallel electrodes.
- **$V \geq V_{cr}$ ⇒ Collision e-N (N: neutral gas density) ⇒ Ionization of neutrals ⇒ 1 ion / 2 free electrons ⇒ Avalanche** (Townsend, 1915).
- $v_{iz} > v_{att}$ ⇒ **Avalanche**
- Free colliding electron frees two electrons from the neutral ⇒ Secondary ionization possible.
- Secondary Electron Emission S.E.E.
  - 'γ' (Bruining, 1954)
  - **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 as reference geometry.
- Not applicable to non-uniform geometries.

Objectives

- Estimates of S.E.E. γ using theory.
- Comparison with experimental data collected in the μTADS chamber.
- Definition of a new system of equations accounting for (1) location between cathode and anode (2) and S.E.E. γ.

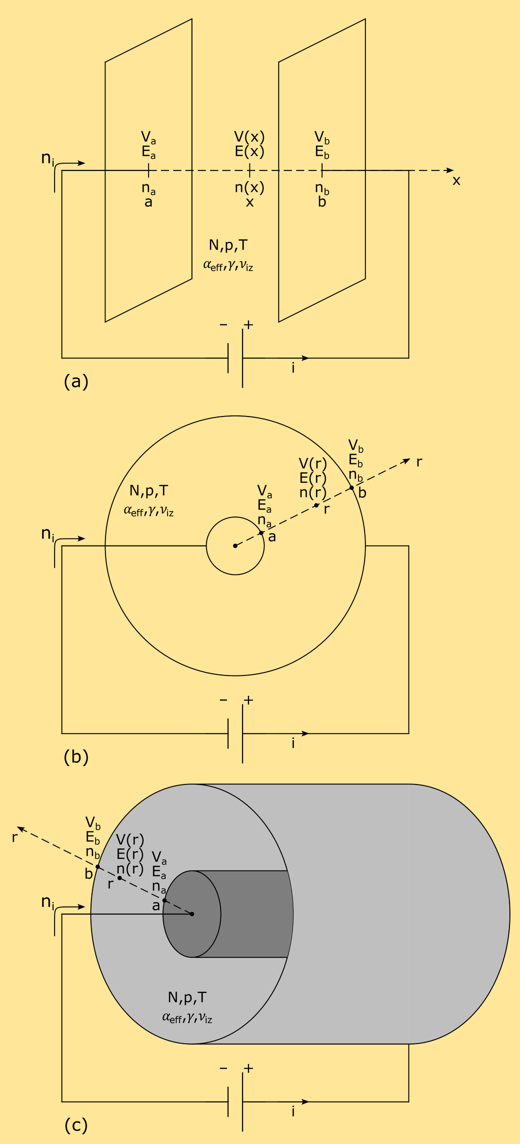
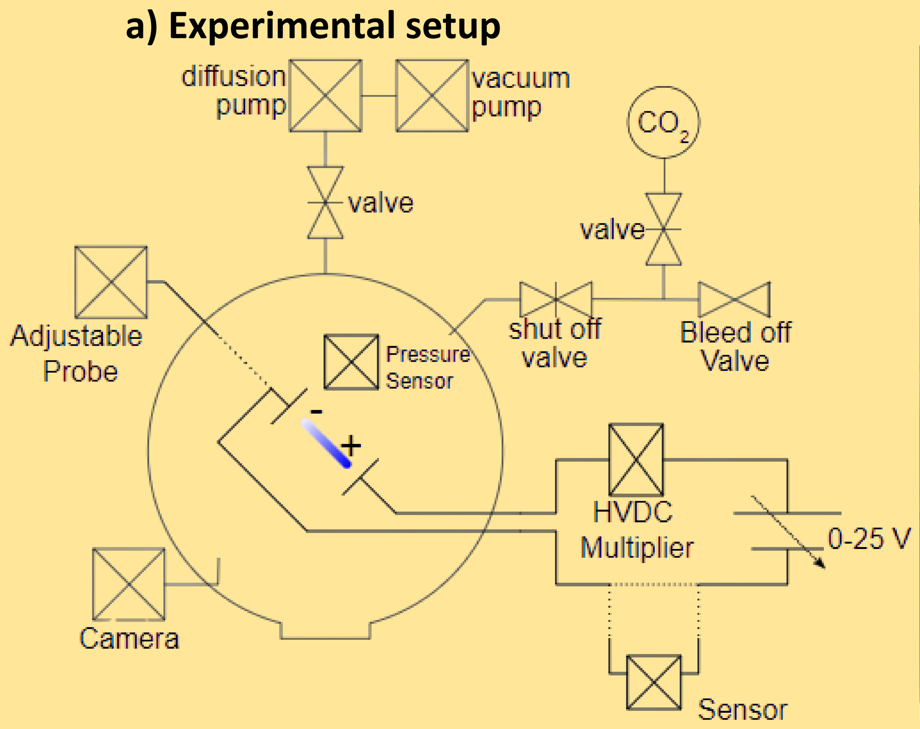


Figure 1 Geometries:
(a) Parallel plates;
(b) Coaxial cylinders;
(c) Concentric spheres

II. Material & Methods

a) Experimental setup



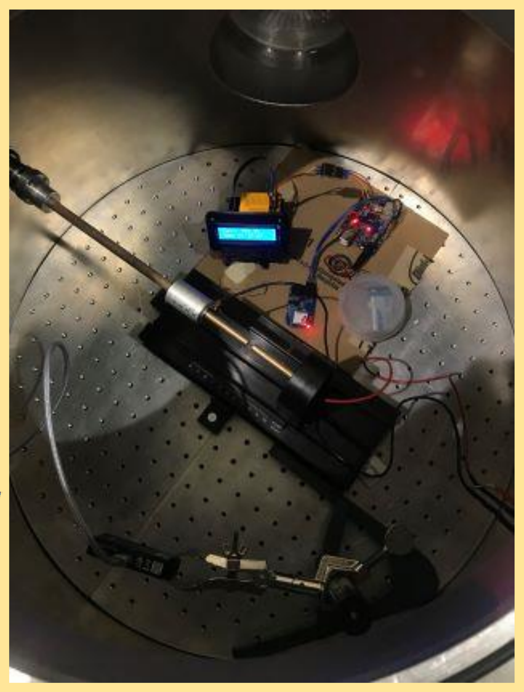


Figure 2 Experimental setup for initiating electrical discharges in air and CO_2. HVDC multiplied input voltage amplifies 0-25V to 10–3000V. Left: Schematic of the entire experimental setup. Right: Inside view of μTADS chamber.

II. Material & Methods (cont.)

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 and V(r) ⇒ Breakdown equation to be solved for $\frac{E}{N}$:

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

- $\delta = 0$: Cartesian ⇒ Engel-Steenbeck solution.
- $\delta = 1$: Cylindrical.
- $\delta = 2$: Spherical.

III. Results

a) Theory

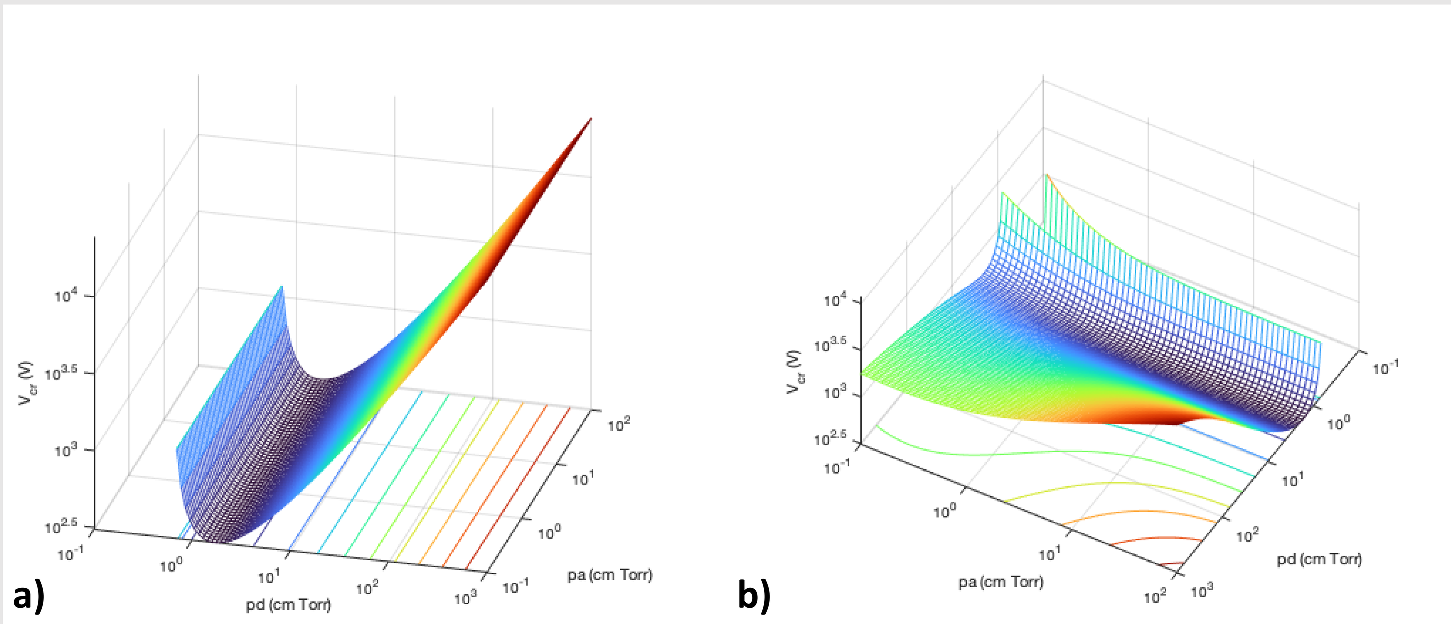


Figure 3 Theoretical plots: (a) Cartesian and (b) cylindrical Paschen curves using newly formulated equations.

b) Experiments

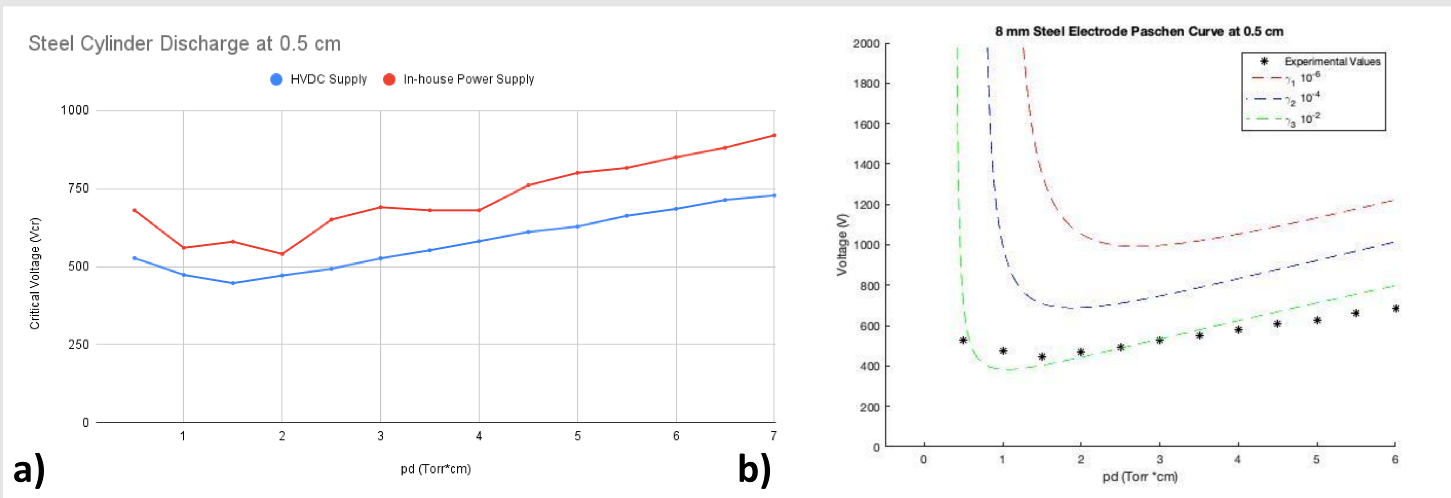


Figure 4 (a) Experimental curves of glow and arc discharges in air. (b) Experimental values and accepted S.E.E values.

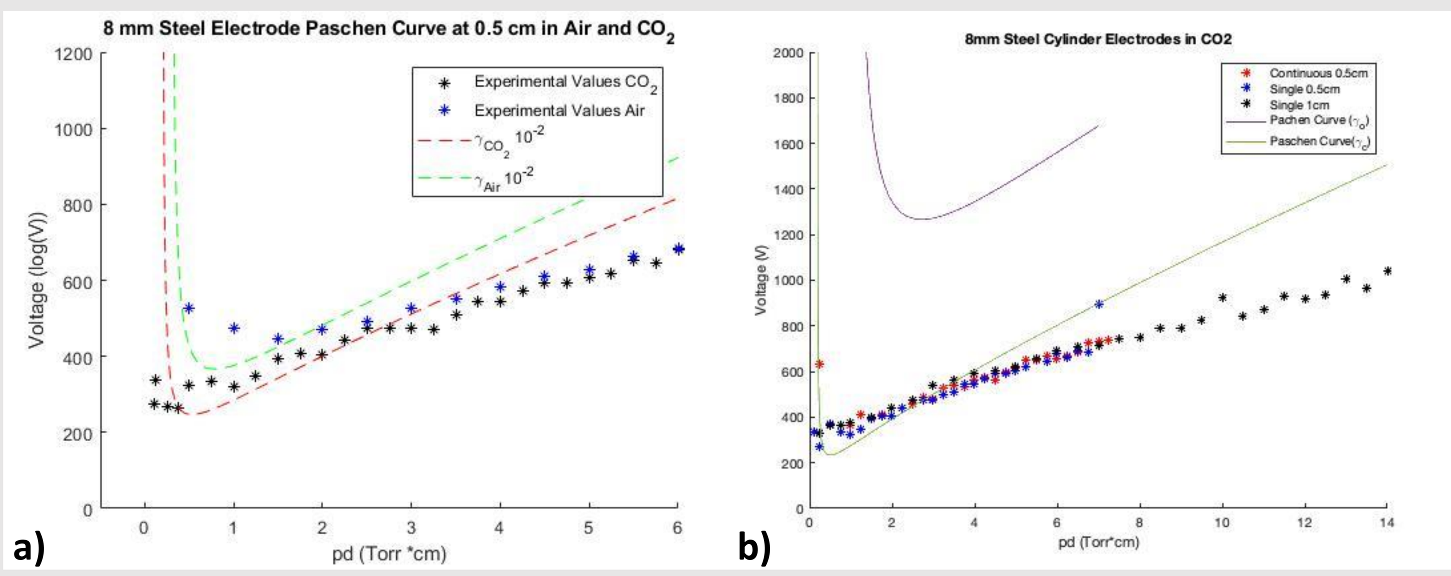


Figure 5 (a) Experimental curves of glow discharges in air and CO_2. (b) Experimental curves for 0.5 cm and 1 cm electrode separation in CO_2.

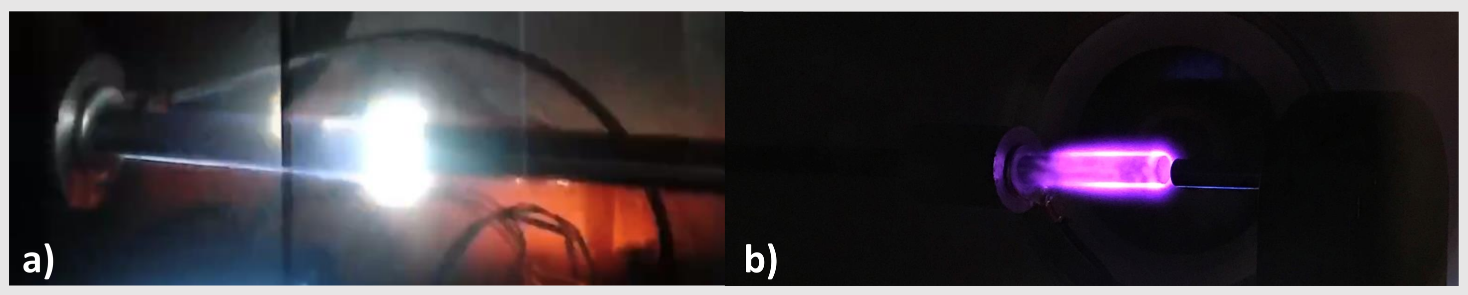


Figure 6 (a) Arc discharge; (b) Glow discharge.

IV. Discussion

Role of power supply (Figure 4a):

- In-house supply (rectified voltage) ⇒ Higher V_{cr} ⇒ **Spark.**
- HVDC ⇒ Lower V_{cr} ⇒ **Glow discharge.**
- Similar trends in both with noticeable shifts.

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}.

Role of Secondary Electron Emission (S.E.E) γ:

- Critical for theory (Figure 4b & 5b).
- S.E.E $\gamma_1 = 0.3 \cdot 10^{-6}$ (Green line in Figure 4b) when computed with the Engel-Steenbeck equation.

Applications:

- Paschen curves = Standard model for dimensioning resistance to dielectric breakdown (e.g., in car batteries).
- Batteries ⇒ **Parallel plate = oversimplification.**
- Increased production of electric cars ⇒ Accrued necessity to understand electrical failures
- Multiple reports of electric car battery failures:
  - Possible link to high voltage battery cells.
  - Li-ion battery cells prone to internal short circuits.
  - Car fires through a thermal runaway effect (Kim, et al., 2020).
- Short circuit events ⇒ High amounts of energy in a short period of time ⇒ Electrical discharges.
- Example: **Car fires** in California ⇒ True nature and danger of the possibility of electric discharges in cars (Faiz, 2021).

V. Conclusion

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

- Development of new formalism for Paschen's law with respect to geometric orientation and metal type.
- Development of new experimental procedures for creating self-sustained electrical discharges in Earth's and Mars' atmosphere.
- Application of theoretical calculations to experimentally found critical voltage V_{cr} inconsistent with previously accepted Paschen's curves.
- Use of theory vs experiment to evaluate secondary ionization coefficients for various materials.

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Acknowledgements

The authors acknowledge support from the National Science Foundation under grant 2047863 to Florida Institute of Technology and travel grant from CEDAR.