Revision of Paschen's Law Relating to the ESD of Aerospace Vehicle Surfaces

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Introduction

- The purpose of this work is to develop a form of Paschen's law that takes into account the flow of gas past electrode surfaces.
- This work was performed under a NASA Science Innovation Fund (SIF) project at the Kennedy Space Center in collaboration with the University of Central Florida.
- In 2010 the Electrostatics and Surface Physics Laboratory (ESPL) at the Kennedy Space Center performed an electrostatic safety analysis on the flight termination system (FTS) antenna for the Ares I rocket.*
- Paschen's law, derived by Friedrich Paschen in 1889 to relate sparking voltage to gas pressure and electrode separation, does not take into account the effect of flowing gas between the electrodes.
- The safety of the FTS housing to triboelectric charging was shown only after extensive laboratory testing.

*M. Hogue, C. Calle, ESPL Report, "Electrostatic Evaluation of the ARES I FTS Antenna Materials", ESPL-TR10-002, August 27, 2010. NASA, Kennedy Space Center.

Introduction

- Potential benefits of a form of Paschen’s law that considers gas velocity.
  - Applicable to current and planned rockets and aerospace vehicles.
  - Possible relaxation of electrostatic launch criteria. Launch aborts can cost up to about a million US dollars depending on the vehicle.

Theoretical Development

- This effort is a first approximation at deriving a generalized form of Paschen’s law to include gas velocity.
- We have theoretically derived a candidate revision of Paschen’s law.
  - Uses the Mach number as a mitigating factor on the number of electron – ion pairs between the electrodes.
  - Compressible dynamic pressure terms were incorporated.
  - Hypothesized an apparent discharge path along the velocity profile.

Paschen’s Law

- Paschen’s law

$$V_s = \frac{\frac{V_i}{LP_a}Pd}{ln(Pd) - ln\left[LP_a ln\left(1 + \frac{1}{\gamma}\right)\right]}$$

- Nomenclature:

V_s	Sparking discharge potential (Volts)
V_i	Ionization potential of the ambient gas (Volts)
P	Gas pressure (torr)
d	Electrode separation (cm)
P_a	Atmospheric pressure at sea level (760 torr)
L	Mean free path at sea level (6.8×10^{-6} cm)
γ	Secondary electron emission coefficient of the electrode metal

Mach Number Formulation

- Hypothesis: The loss of electron – ion pairs due to gas velocity can be expressed by a dimensionless aerodynamic term such as the Mach number.
- The model equation must revert to Paschen's law when the mean gas velocity, $v_{\mathrm{xm}} = 0$.
- The Mach number is the ratio of the mean gas velocity to the speed of sound, $M_{\mathrm{N}} = v_{\mathrm{xm}}/c$. Here c = 319 m/s at sea level.
- Using the Mach number to mitigate the concentration of electron – ion pairs in the derivation of Paschen's Law we have

$$V_s = \frac{\frac{V_i}{LP_a}(Pd)}{ln(Pd) - ln\left[LP_a ln\left(1 + \frac{1}{\gamma}\right)\right] - M_N}$$

- This equation reverts to Paschen's law when $v_{\mathrm{xm}} = 0$.

Mach Number and Compressible Dynamic Pressure

- For moving vehicles, pressure has two components
  - Static pressure: P_s
  - Compressible dynamic pressure: P_{DC}
- Above Mach 0.3 the compressible form of the dynamic pressure must be used.

$$P_{DC} = P_s\left[\left(1+\frac{\gamma_a-1}{2}M_N^2\right)^{\frac{\gamma_a}{\gamma_a-1}}-1\right]$$

$\gamma_a \equiv$ Ratio of Specific Heats = C_P/C_V

- Total pressure

$$P = P_s + P_{DC} = P_s + P_s\left[\left(1+\frac{\gamma_a-1}{2}M_N^2\right)^{\frac{\gamma_a}{\gamma_a-1}}-1\right]$$

$$P = P_s\left(1+\frac{\gamma_a-1}{2}M_N^2\right)^{\frac{\gamma_a}{\gamma_a-1}}$$

Mach Number and Compressible Dynamic Pressure

- Substituting the total pressure in the model equation gives for the sparking voltage

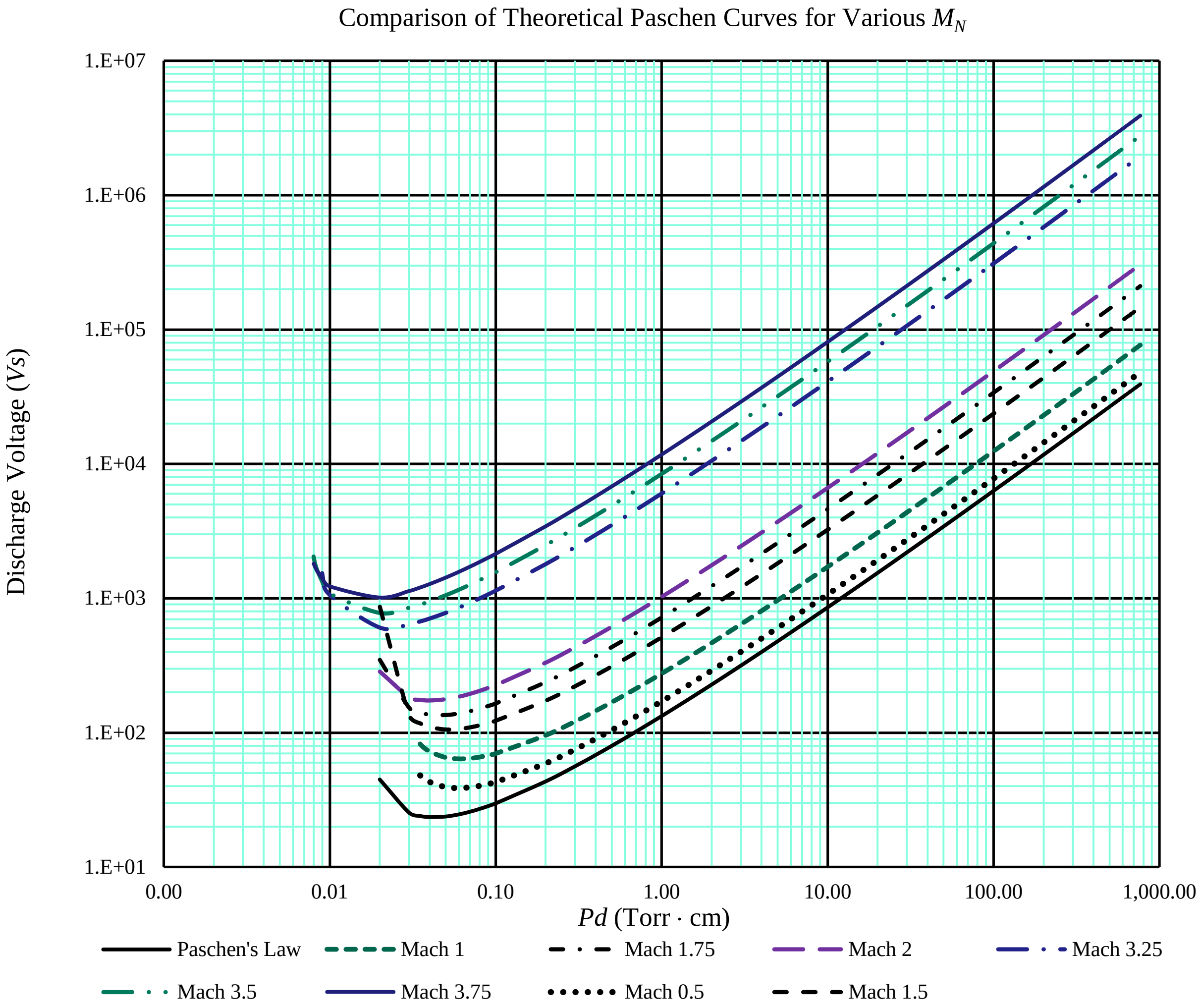
$$V_s = \frac{\frac{V_i}{LP_a}\left(1 + \frac{\gamma_a - 1}{2} M_N^2\right)^{\frac{\gamma_a}{\gamma_a - 1}} P_s d}{ln\left[\left(1 + \frac{\gamma_a - 1}{2} M_N^2\right)^{\frac{\gamma_a}{\gamma_a - 1}} P_s d\right] - ln\left[LP_a ln\left(\frac{1}{\gamma} + 1\right)\right] - M_N}$$

- This equation also meets the requirement that Paschen's law is returned when the mean gas velocity is zero.
- In this equation, the sparking voltage is a function of three variables: static pressure, electrode separation, and Mach number

$$V_s = f(P_s, d, M_N)$$

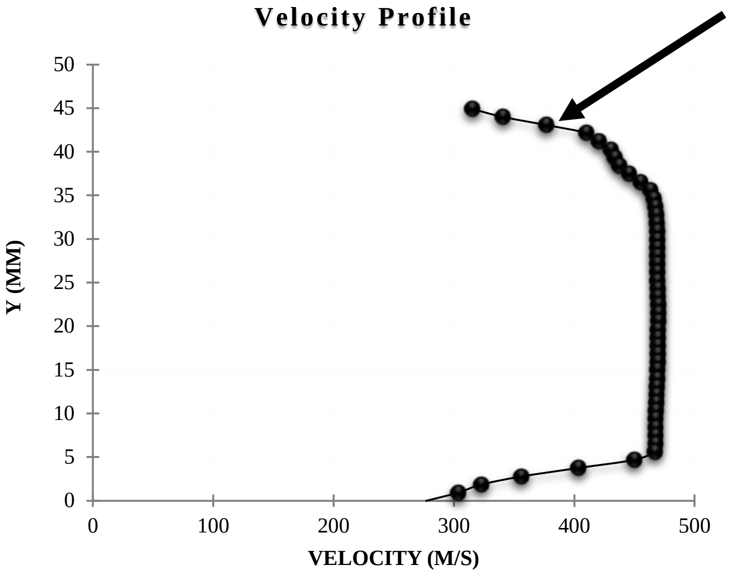
Theoretical Comparison

The model equation is graphed for stainless steel electrodes ($\gamma = 0.02$) at various Mach numbers for air ($\gamma_a = 1.4$) between 0.5 and 3.75 and a gap of 1.3 cm.



A Hypothesized Effective Discharge Path

Gap: 4.4 cm, Gas: air, Gas velocity: Mach 1.47



Length of velocity profile measured to be ~ 11.7 cm from full scale print.

Wind tunnel velocity profile data provided by UCF.

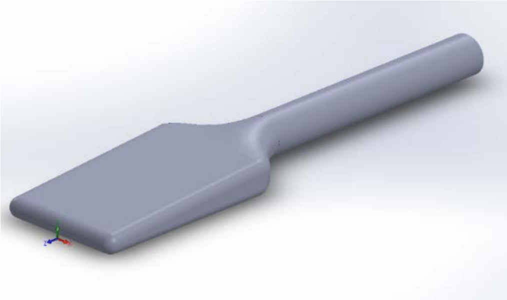
- From inspection of the model equation, we can hypothesize an effective electrode separation

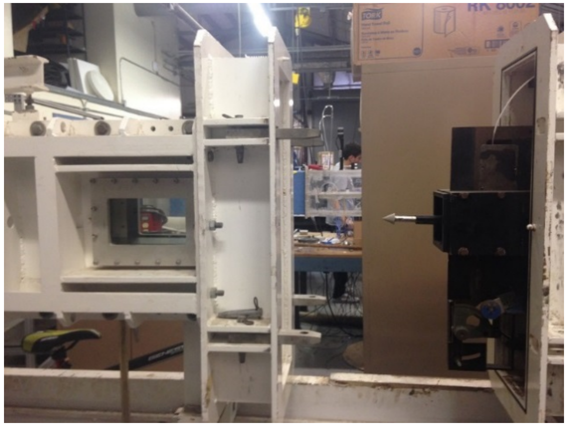
$$d' = \left(1 + \frac{\gamma_a - 1}{2} M_N^2\right)^{\frac{\gamma_a}{\gamma_a - 1}} d$$

- For air: γ_a = 1.4. At Mach 1.47 and d = 4.4 cm this gives a value of d' of 15.48 cm or only about 25% larger than the measured value.
- Additional experiments will be needed to better evaluate this hypothesis.

Description of Wind Tunnel Experiments

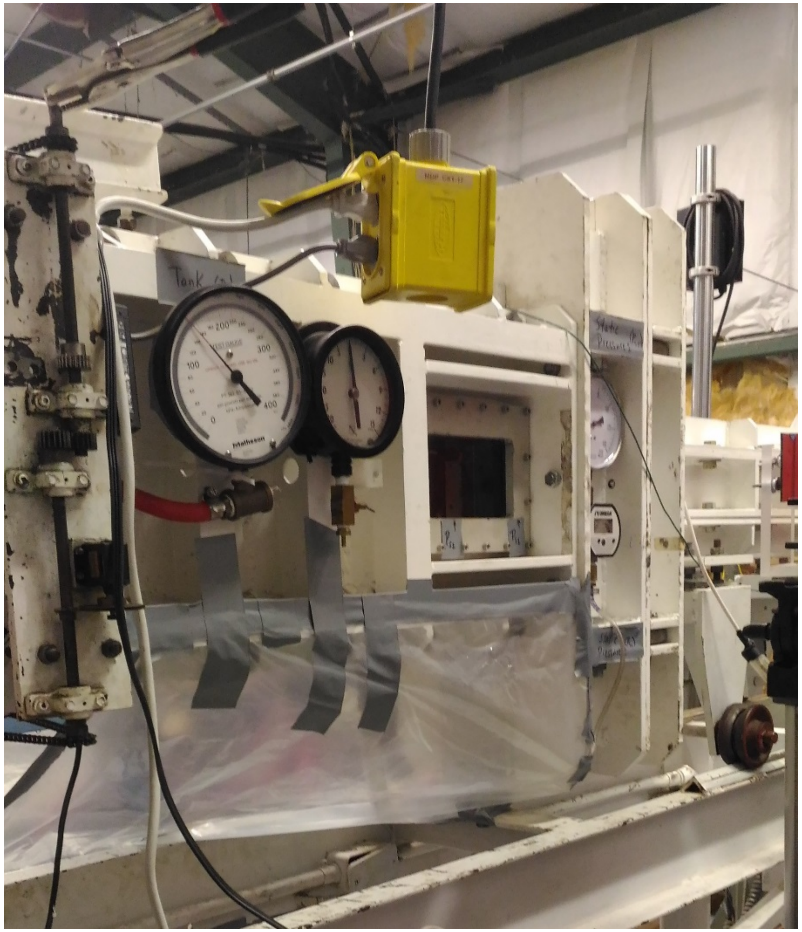
- Wind tunnel experiments were performed at the Florida Center for Advanced Aero-Propulsion (FCAAP) of the University of Central Florida (UCF)
- An existing wind tunnel was modified to incorporate a stainless steel electrode plate attached to a movable sting mount in the test section.



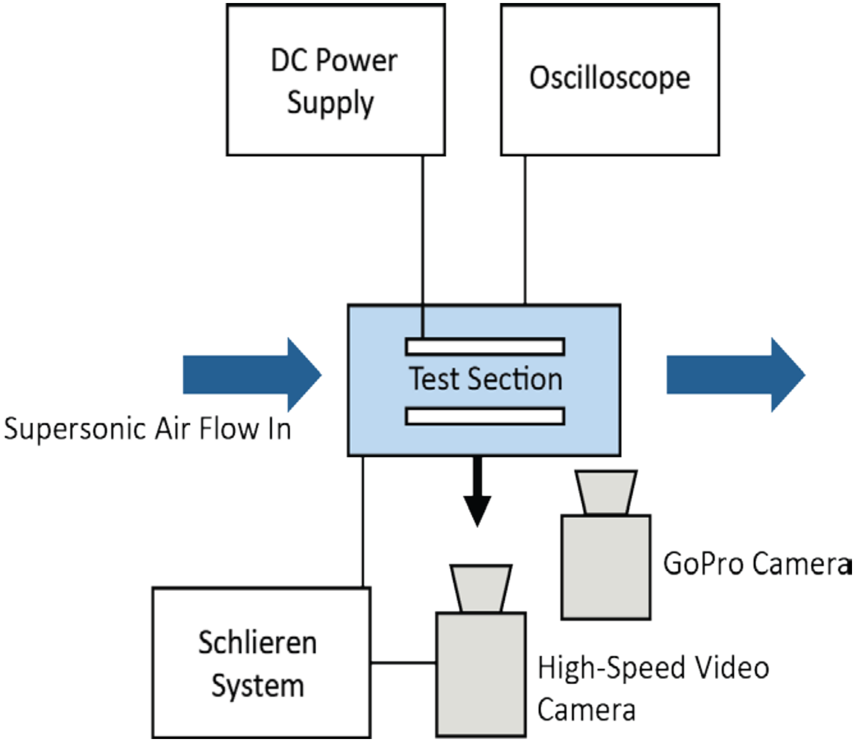


Description of Wind Tunnel Experiments

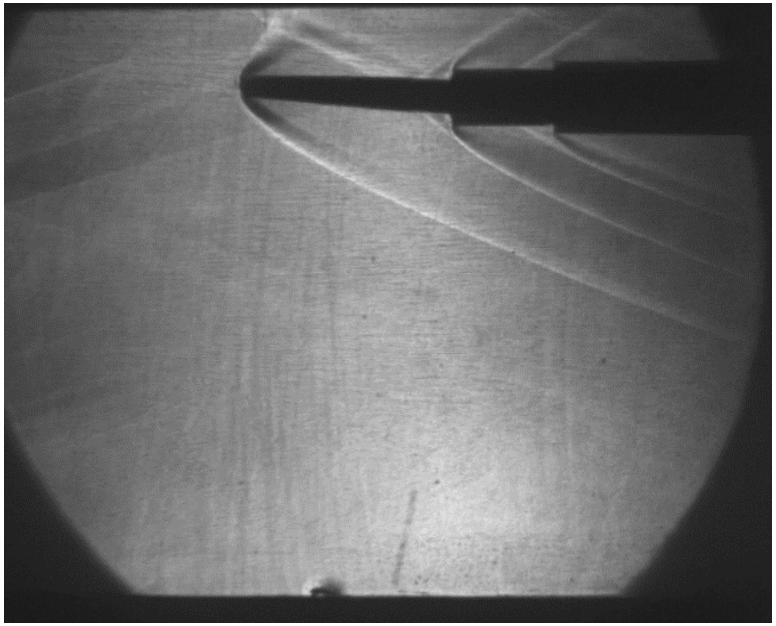
- The upper portion of the test section was also made from stainless steel and acted as the ground plate.
- 1.3 cm was the closest the electrode could be physically placed to the stainless steel upper surface.
- The test section was instrumented to input DC voltage to the electrode, measure static pressure, P_s, mean velocity, v_{xm}, and to provide video of the experiment.
- A high speed camera was used with a Schlieren system to capture images of the supersonic shocks around the electrode.



Description of Wind Tunnel Experiments



High level schematic of the wind tunnel experimental setup.



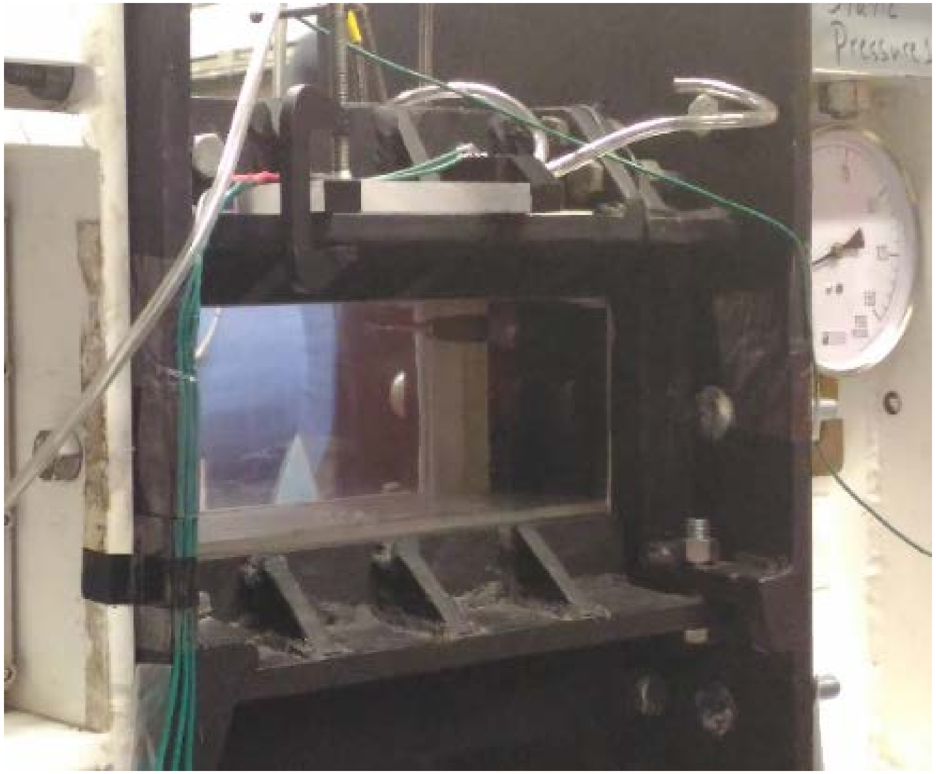
Typical shocks around the electrode. Mach 3.5

Description of Wind Tunnel Experiments

- Two types of experiments were performed.
  - Under steady supersonic flow, the electrode voltage was ramped up to observe and record any sparking.
  - Preload the electrode to achieve sparking during no-flow conditions, then turning on the wind tunnel to observe the effects of the supersonic flow.
- The voltage ramping experiments were difficult
  - short duration of steady supersonic flow (< 30 seconds)
  - shock reflections between the electrode and the wall of the test section affected pressure measurements.
  - High voltage supply was limited to about 35 kV due to the rating on the high voltage cabling that could fit through the sting mount.

Description of Wind Tunnel Experiments

- A new instrumented test section was attached to the wind tunnel.
  - Pressure sensing port located to more accurately measure static pressure between the electrodes.
  - Located further down the tunnel to mitigate air turbulence.
- Experiments were run at Mach 1.65 for this test section.



Experimental Data

- Video data shows sparking quenched by the onset of supersonic flow consistent with the theoretical model.

Sparking

Start of supersonic flow

Sparking quenched

Sparking resumes after supersonic flow ends

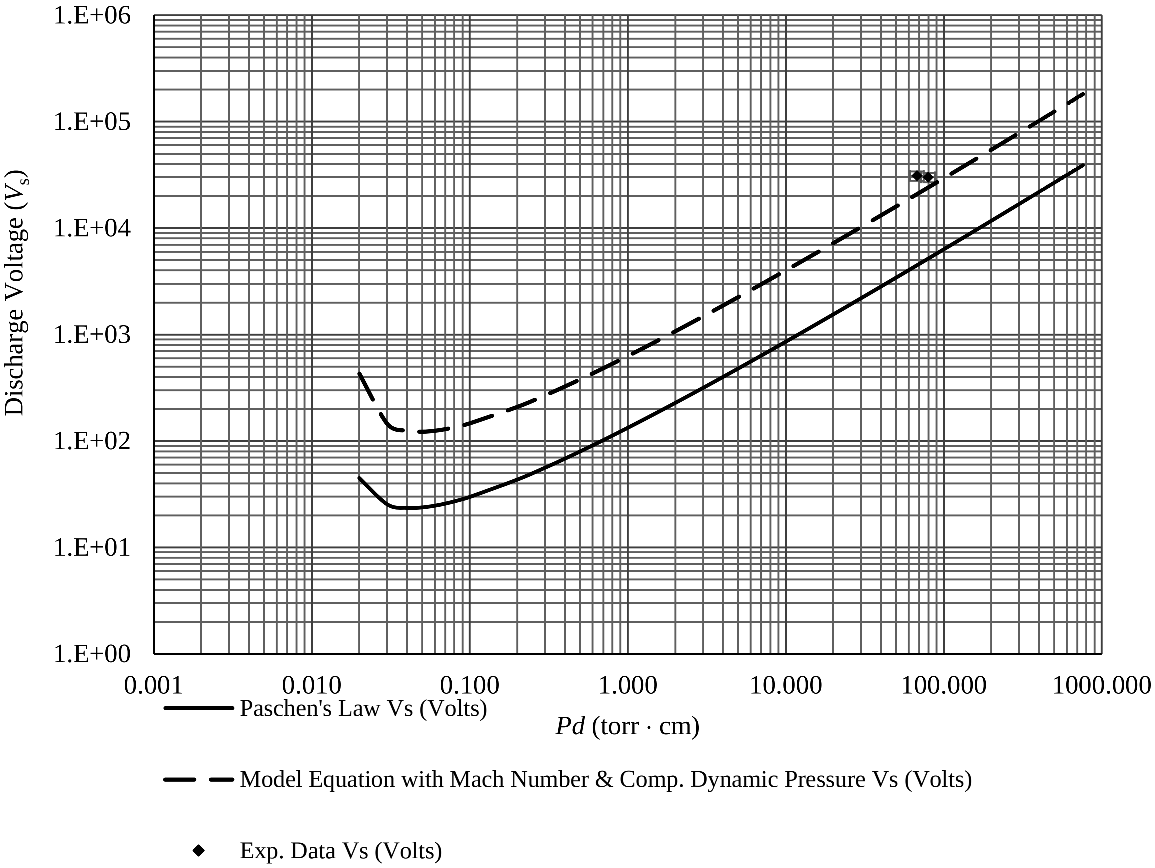
← Air flow direction

- Noted that the shape of the deformation of the spark prior to quenching is convex in appearance.

Experimental Data

- Two of the eleven Mach 1.65 experiments yielded measurable sparks during supersonic flow.
- These two data points compare well to the theoretical model with both the Mach number and compressible dynamic pressure terms.

Model Equation Comparison to Paschen's Law and Experimental Data (Mach 1.65, *d* = 1.3 cm)



Future Work

- Recent award of a FY 2019 Center Innovation Fund (CIF) project is continuing this work (project start 3/1/19).
- Theoretical work underway to put the model equation into a form that includes ambient temperature.
- New wind tunnel experiments under design
  - Develop LabView™ control program
  - Design and fabricate new wind tunnel test sections to lessen shock reflections. The upper and lower panels will be the HV electrode and ground respectively.
  - Both voltage ramp and spark quenching experiments planned.
  - Gather more velocity profile data to better evaluate the hypothesized effective discharge distance.

Summary

- A first approximation theoretical model equation based on Paschen’s law was developed to account for the effect of gas flow on the sparking voltage.
- An effective discharge distance due to gas velocity was hypothesized based the theoretical model and limited wind tunnel test data.
- Wind tunnel experiments were conducted that gave results consistent with the prediction of the model equation.
- Further theoretical revision of the model equation and wind tunnel experimentation via a KSC CIF project are underway.

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