An Experimental Validation of a Revised Paschen's Law Relating to the ESD of Aerospace Vehicle Surfaces

André Woodard[1], Manuela Morales[2], Jonathan Sosa[3], and Kareem A. Ahmed[4]
University of Central Florida, Orlando, Florida, 32816, USA

Michael R. Johansen[5], Jennifer G. Wilson[5], and Michael D. Hogue[5]
Flight Technology Branch, UB-R2, NASA, Kennedy Space Center, FL, 32899, USA

Seth A. Rhodes[6]
The Bionetics Corporation, LASSO-6720, Kennedy Space Center, FL, 32899, USA

This work seeks to experimentally validate a modified Paschen law which takes into account the effects of electron-ion pair removal between two electrodes within a dynamic gas medium. A test facility has been designed and fabricated in order to create supersonic flow conditions within the test section. Custom designed electrodes are mounted into the test section at desired gap distances. A power supply is utilized to charge the electrodes until discharge occurs. The discharge voltage of the electrode is recorded over a range of pressures within the test section. An operational pressure range is calculated using isentropic flow and normal shock relations at the desired Mach numbers. These values are plotted against the modified Paschen curve as a function of Mach number, electrode gap distance, and pressure as a means of validation.

I. Nomenclature

V_s	=	sparking discharge voltage
V_i	=	ionization potential of ambient gas
P	=	stagnation pressure of gas [Torr]
P_{atm}	=	pressure of gas at sea-level [Torr]
γ	=	secondary electron emission of electrode material
L	=	molecular mean free path at sea level [cm]
d	=	gap between electrodes [cm]
γ_a	=	specific heat ratio of air

---

[1] Graduate Research Assistant, Mechanical and Aerospace Engineering, AIAA Student Member.
[2] Undergraduate Research Assistant, Mechanical and Aerospace Engineering, AIAA Student Member.
[3] Postdoctoral Scholar, Mechanical and Aerospace Engineering, AIAA Member.
[4] Assistant Professor, Mechanical and Aerospace Engineering, AIAA Associate Fellow.
[5] Flight Technology Branch, UB-R2, Kennedy Space Center, FL.
[6] LASSO-6720, The Bionetics Corporation, Kennedy Space Center, FL.

II. Introduction

Electrostatics is the study of static potential fields. The potential fields under investigation span multiple applications such as microelectromechanical systems (MEMS) [1,2], aerospace systems [3,4], and even space physics [5]. An understanding of electrostatics can also help mitigate hazards and increase the lifespan of electrical components [6,7]. One important relationship in electrostatics is Paschen's law, which relates the discharge voltage of a material in a gas medium to the gap distance and gas pressure. Paschen's law was utilized by Cotton et.al. to verify the minimum voltage at which a discharge will occur across an air gap between aircraft electrical components [3]. The purpose of Cotton's work was to discuss the challenges faced with the necessity of a higher voltage supply when replacing mechanical aircraft systems with electrical systems. Given that Paschen's law was derived for a stationary gas medium, there is a void in understanding of the corresponding discharge voltage in a dynamic gas medium. Sickafoose et. al. has shown that dust particles can be triboelectrically charged [8]. Thus, the microscopic dust particles that exist in Earth's atmosphere may be triboelectrically charged by aerospace vehicles in flight. The charged particles become a risk of causing an electrostatic discharge (ESD) between the particles on the vehicle surface and the particles in the atmosphere. An ESD on the vehicle surface can cause damage to aerospace vehicles and lead to in-flight complications [9,10]. Therefore, an accurate relationship for the discharge voltage in a dynamic gas medium is necessary for the success of aerospace vehicles. Hogue et. al. developed a modified version of Paschen's law which accounts for the effects of gas flow between two electrically charged electrodes [11]. Experimental work was conducted at the University of Central Florida (UCF) Center for Advanced Turbomachinery & Energy Research (CATER) lab to validate the revision of Paschen's law [12]. Though the preliminary data showed to be consistent with the revised Paschen law, the data was constricted to a small range of pressures, limiting its range of validation. Additionally, undesired shock reflections existed within the test section which led to untrustworthy pressure measurements. The scope of this work is to validate the revised Paschen law in ideal flow conditions over a wider pressure range.

By defining a sound relationship between the discharge voltage, pressure, and electrode gap distance, scientists will be able to better predict atmospheric conditions that will result in an ESD. A valid relation describing the discharge voltage between particles in a dynamic gas medium can also lead to preventative product development. With the current boom in the commercial space economy, the demand for accessibility to space is rising. With this rise, the financial impact of scrubbed launches becomes more detrimental. This work will save companies an appreciable amount of resources by relaxing the launch commit criteria related to triboelectric charging from atmospheric debris.

III. Experiment

This study was conducted in the Propulsion & Energy Research Laboratory (PERL) at UCF using a custom designed supersonic test facility. Air is pushed through a constant area inlet channel into a converging-diverging (CD) nozzle. The CD nozzles were designed using a method of characteristics used in [13] to produce Mach 1.5 and Mach 2 flow. The nozzle exit area A_e to throat area A^* ratio was calculated using the isentropic flow relation [14]

$$\frac{A_e}{A^*} = \frac{1}{M_e}\left[\left(\frac{2}{\gamma_a + 1}\right)\left(1 + \frac{\gamma_a - 1}{2} M_e{}^2\right)\right]^{\frac{\gamma_a+1}{2(\gamma_a-1)}} \tag{1}$$

where M_e is the targeted Mach number. After expanding through the CD nozzle, the air then flows between two custom designed electrodes in the test section. A power supply is used to charge the electrodes until a discharge occurs between them. The results of this work demonstrate a revised Paschen law which accounts for the removal of electron-ion pairs by gas flow between two charged particles.

A. Theoretical Background

Paschen's law defines the relationship between the discharge voltage of two electrodes in a gas medium as a function of the gas's stagnation pressure and the distance between electrodes, namely [11]

$$V_s = \frac{\frac{V_i}{L\,P_a}(Pd)}{\ln(Pd) - \ln\left[LP_a \ln\left(1 + \frac{1}{\gamma}\right)\right]} \tag{2}$$

Given that Paschen's law was derived for a stationary gas medium, the stagnation pressure term P simplifies to the static pressure of the gas. A strict requirement of the revision is that it must simplify to the original Paschen law when the gas medium is stagnant. Hogue et.al. derived a formulation that accounts for the effects of the compressible dynamic pressure of the flow yielding a revised Paschen law [11]

$$V_s = \frac{\frac{V_i}{L\,P_{atm}}(1+\frac{\gamma_a-1}{2}M^2)^{\frac{\gamma_a}{\gamma_a-1}}Pd}{\ln\left[(1+\frac{\gamma_a-1}{2}M^2)^{\frac{\gamma_a}{\gamma_a-1}}Pd\right]-\ln\left[LP_{atm}\ln\left(1+\frac{1}{\gamma}\right)\right]-M} \tag{3}$$

To achieve the targeted pressure range, isentropic flow and normal shock relations are utilized. Given that the proposed facility exhausts to atmospheric conditions, the flow needs to be ideally expanded in order to obtain atmospheric pressure with the test section. The required stagnation pressure is then defined by the isentropic flow relation [14],

$$\frac{P}{P_a} = \left(1+\frac{\gamma_a-1}{2}M^2\right)^{\frac{\gamma_a}{\gamma_a-1}} \tag{4}$$

where P_a is the ambient pressure within the test section. For the ideally expanded case, $P_a = P_{atm}$ is the maximum pressure value desired. The normal shock relation [14] defines the minimum test section static pressure for each case by

$$\frac{P_{atm}}{P_a} = \frac{2\gamma_a M^2}{\gamma_a+1} - \frac{\gamma_a-1}{\gamma_a+1} \tag{5}$$

B. Facility Design

The designed test facility consists of an inlet, expansion, and test section as shown in Fig. 1. The facility is designed to allow the expansion and test section to be interchanged for each test case. Four CD nozzles are fabricated in order to properly expand the flow for each test condition. The CD nozzles were designed with an inlet height of 100 mm (3.937 in). The facility was designed to satisfy a contraction ratio of at least 2 between the inlet area and throat area of the CD nozzle to minimize pressure losses [16,17]. A summary of the CD nozzle critical dimensions is given in Table 1. To ensure proper expansion occurs within the CD nozzle, pressure transducers are mounted in both the inlet and test section of the facility. The nozzle contours for each test case are depicted in Fig. 2.

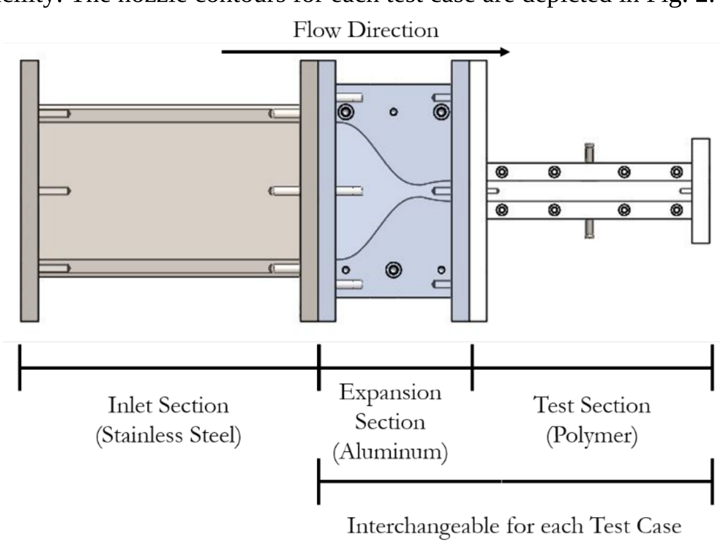


Fig. 1 Overview of Experimental Facility

Table 1 CD Nozzle Critical Dimensions

Test Case	Inlet Height [mm]	Mach Number	Gap Distance [mm]	Throat Diameter [mm]
1	100	1.5	10	8.502
2			15	12.753
3		2.0	10	5.926
4			15	8.889

Custom designed electrodes are mounted to the top and bottom of the test section at the desired gap distance. The electrodes were designed such that a spark plug cap could be used to transmit the voltage from the power supply. To avoid shock waves within the test section, the head of the electrodes were designed with a highly elliptic contour which intrudes into the flow a depth of 0.007 in. The test section is fabricated out of Lexan polycarbonate to ensure that the high voltage is contained within the test section.

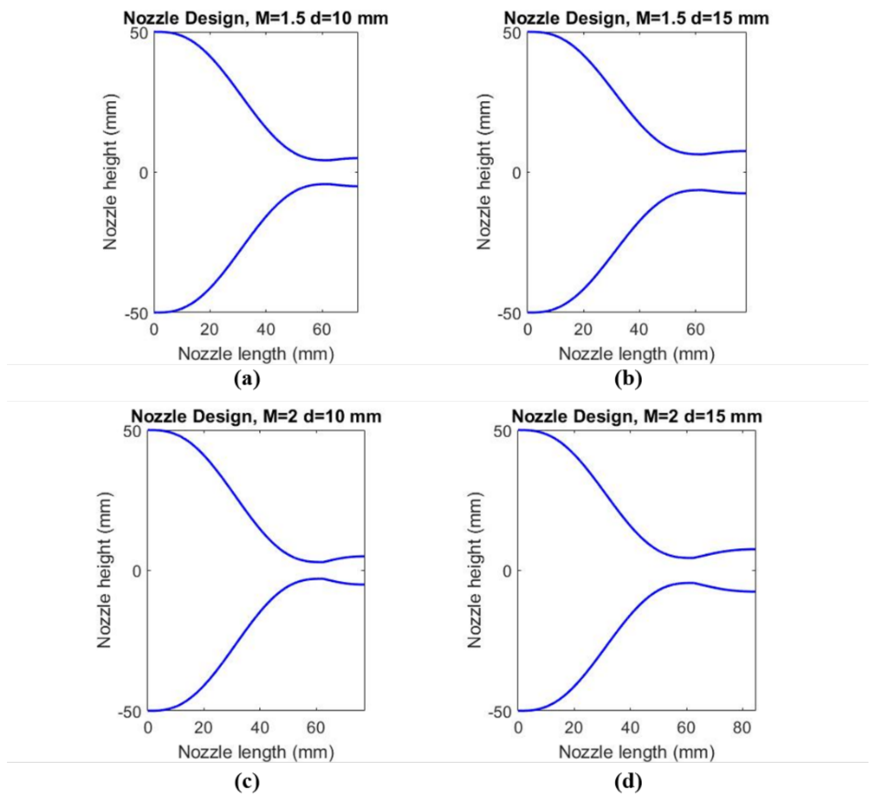


Fig. 2 CD Nozzle Contours for each Test Case

C. Experimental Procedure

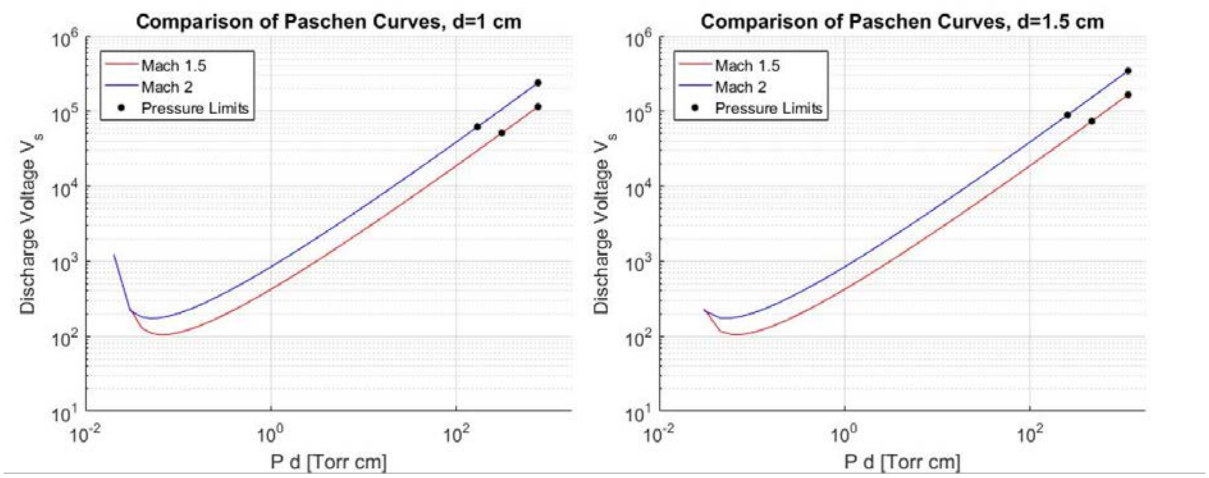
Paschen's law is to be validated at two Mach numbers and two electrode gap distances. The experimental facility runs off of an air reservoir consisting of 32 48-liter tanks. A Glassman 60kV Series EH power supply is used to charge the electrodes. To find the sparking voltage of a defined pressure, air is supplied to the test facility until steady state conditions have been reached. From there, the power supply is progressively ramped up from 0 to 50kV until a discharge occurs. The pressure transducers and power supply are programmed together into LabVIEW. Once sparking occurs between the electrodes, the power supply shuts off and the corresponding voltage and pressure values are recorded by an NI cDAQ-9174. A GoPro and Photron SA1.1 high speed camera are used to capture the discharge between the electrodes as a means of verification. The procedure is repeated at different pressures within the targeted pressure range. A summary of the targeted test conditions is shown in Table 2.

Table 2 Targeted Test Conditions

Test Case	Mach Number	Gap Distance [mm]	Min Static Pressure [Torr]	Max Static Pressure [Torr]
1	1.5	10	309.15	760
2		15		
3	2.0	10	168.89	
4		15		

Results and Conclusions

Based on preliminary data, the modified Paschen law is consistent with experimental results. Figures 3.a and 3.b illustrate the range of values that the revised Paschen law is validated over. Experimentation is ongoing to obtain data points towards the lower limits of the pressure range.



(a) (b)

Fig. 3 Pressure Limits of Results at a) 1 cm electrode gap b) 1.5 cm electrode gap

Acknowledgments

The PERL at UCF would like to thank Dr. Michael Hogue and staff of ESPL at Kennedy Space Center (KSC) for the funding of this work and its continuing collaboration.

References

[1] Livermore, C., Forte, A., Lyszczarz, T., Umans, S. D., & Lang, J. H. (2003). Microscale electric induction machines for power applications. Electrostatics.

[2] B. R. Donald, C. G. Levey, C. D. McGray, I. Paprotny and D. Rus, "An untethered, electrostatic, globally controllable MEMS micro-robot," in Journal of Microelectromechanical Systems, vol. 15, no. 1, pp. 1-15, Feb. 2006. doi: 10.1109/JMEMS.2005.863697

[3] Cotton, Ian, Andrew Nelms, and Mark Husband. "Higher voltage aircraft power systems." IEEE Aerospace and Electronic Systems Magazine 23.2 (2008): 25-32.

[4] Cotton, A. Nelms and M. Husband, "Defining safe operating voltages for aerospace electrical systems," 2007 Electrical Insulation Conference and Electrical Manufacturing Expo, Nashville, TN, 2007, pp. 67-71. doi: 10.1109/EEIC.2007.4562590

[5] Melnik, Olga, and Michel Parrot. "Electrostatic discharge in Martian dust storms." Journal of Geophysical Research: Space Physics 103.A12 (1998): 29107-29117.

[6] Ackroyd, G. P., and S. G. Newton. "An investigation of the electrostatic ignition risks associated with a plastic coated metal." Journal of electrostatics 59.2 (2003): 143-151.

[7] Nifuku, M., et al. "Explosibility of shredder dusts for electrical appliances." CONFERENCE SERIES-INSTITUTE OF PHYSICS. Vol. 178. Philadelphia; Institute of Physics; 1999, 2004.

[8] Sickafoose, A. A., et al. "Experimental investigations on photoelectric and triboelectric charging of dust." Journal of Geophysical Research: Space Physics 106.A5 (2001): 8343-8356.

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

[10] J. E. Nanewicz, AFAL-TR-73-317, Flight Evaluation of Induced-Noise Mechanisms on High Speed Aircraft, Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio, October, 1973.

[11] Hogue, M. D., Cox, R. E., Mulligan, J., Kapat, J., Ahmed, K., Wilson, J. G., & Calle, L. M. (2017). Revision of Paschen's Law Relating to the ESD of Aerospace Vehicle Surfaces.

[12] Hogue, M. D., Cox, R. E., Mulligan, J., Ahmed, K., Wilson, J. G., & Calle, L. M. (2018). Dynamic gas flow effects on the ESD of aerospace vehicle surfaces. Journal of Electrostatics, 91, 21-27.

[13] Sosa, J., Ahmed, K. A., Fievisohn, R., Hoke, J., Ombrello, T., & Schauer, F. (2019). Supersonic driven detonation dynamics for rotating detonation engines. International Journal of Hydrogen Energy, 44(14), 7596-7606.

[14] John, J. E., & Keith, T. G. (2006*). Gas Dynamics*. Upper Saddle River: Pearson Prentice Hall.

[15] Goeing, M. "Nozzle design optimization by method-of-characteristics." 26th Joint Propulsion Conference. 1990.

[16] Morel, Thomas. "Comprehensive design of axisymmetric wind tunnel contractions." Journal of Fluids Engineering 97.2 (1975): 225-233.

[17] Maninder S. Uberoi. "Effect of wind-tunnel contraction on free-stream turbulence." Journal of the Aeronautical Sciences 23.8 (1956): 754-764.