High Voltage Phenomena In Rarefied Air: A DIY Approach

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Abstract

The present experiment aims to recreate and analyze known behavior of high-voltage gaps in a near vacuum with low-cost equipment. It has been previously observed that the application of high voltages in rarified gas results in electrical breakdown and corona discharge, characterized by the production of observable plasma in the experimental area. The current study aims to identify and document a do-it-yourself (DIY) method for producing and containing electrical discharge. Further, the requirements of electrical phenomena were recorded in terms of voltage and pressure to be compared to previous models, namely Paschen's Law, as a measure of accuracy (Berzak et al., 2006). The operating experimental apparatus was demonstrated to exhibit the same discharge phenomena as previously recorded (Peek, 1929). New models for voltage and pressure requirements for electrical breakdown and corona discharge were produced. Literature comparison was available for the voltage model of electrical breakdown, where significant difference was identified between Paschen's model and current data. The present study may contribute further evidence to the inadequacy of Paschen's law in describing breakdown voltages at high pressure-distance configurations.

Introduction

From antique CRT televisions to high-tech ion thrusters, electrical discharge, or a lack thereof, is critical for the operation of modern machinery. Precise control of electrical arcs is thus a fundamental requirement of present day technology, justifying further research on the topic.

The current model for electrical phenomena is based upon the dielectric strength of air (Peek, 1929). At lower voltages, the electric field across two electrodes is sufficiently low for air to act as an insulator. There is no conductance and no electric arc is observed.

As voltage is increased, increased dielectric flux density around the conductors forces the surrounding air to become conductive, forming a film of purple plasma around the active electrodes, named corona discharge (Peek, 1929; Goldman et al., 1985). However, the electrode gap is not yet fully conductive, so no arc is created.

Electrical breakdown occurs when the dielectric strength of the air gap is exceeded. At this voltage, the neutral air molecules in the gap are ionized by the high potential difference, and the air becomes a sea of conductive charges (Bawagan, 1997). At this point, the circuit is completed between the two electrodes, resulting in a bright electrical arc.

The voltage-pressure requirements for electrical discharge is predicted by Paschen's law. Recent experimental evidence has both supported and disputed the accuracy of this model (Lisovskiy et al., 2000; Berzak et al., 2006; Massarcyzk et al., 2016). The current experiment aims to gather further experimental evidence for previously proposed models for electrical breakdown and to produce a novel model fit for the requirements of corona discharge. This study also aims to determine whether a DIY approach to the experimental apparatus is able to yield viable data.

Methods

Measurement Apparatus

A compact fluorescent lamp (CFL) ballast was connected to a flyback transformer to convert AC into high voltage (HV) DC. The input of the ballast is connected to a power cord, and the output to the flyback transformer.The output of the flyback transformer served as one electrode, and the ground as the other.

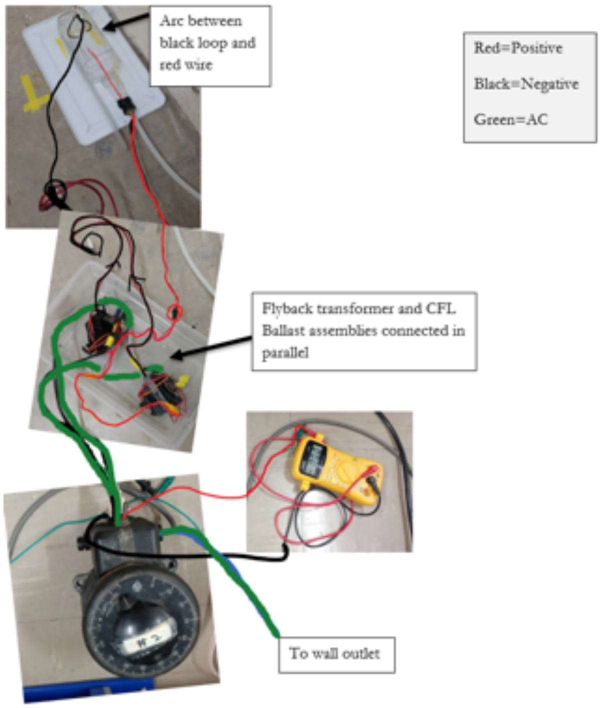

Fig. 1. Experimental apparatus wiring illustration

Two transformers were connected in parallel and plugged into a variac that controlled input AC voltage (VAC).

The vacuum chamber was composed of glass with a 3/8" hole at one end drilled using a ceramic spade bit. A wire bent into a loop of diameter 5cm was inserted and the hole sealed with hot glue to prevent vacuum leaks. The other end of the chamber was held closed by a rubber stopper with a 1/4" hose barb. A wire was attached to the hose barb to act as a point of conduction.

A vacuum pump with a connected 1/4" hose barb was used. A cross with four female NPT threads connected two hose barbs as well as a pressure bleed valve and a vacuum gauge.

Measurements

Corona Discharge Voltage Measurements

Upon reaching an absolute pressure of 11kPa, the input VAC was increased until a glow at the electrodes was observed. The input voltage at which this occurred was recorded. This measurement was performed with both electrode configurations at different electrode gap lengths.

Breakdown Voltage Measurements

Breakdown voltage was defined as the voltage at which an arc is struck between the two electrodes. A pressure of 17kPa was obtained and the input voltage increased until a visible arc was observed. The input voltage at which an arc was observed was recorded. This measurement was performed with both electrode configurations at different electrode gap lengths.

Breakdown Pressure Measurements

Breakdown pressure was defined as the pressure at which an arc is struck between the electrodes at a maximum input of roughly 130VAC (4500VDC). The pressure at which a visible arc is observed was recorded. This measurement was performed with both electrode configurations at different electrode gap lengths.

Results

Indicators of Phenomena

As previously indicated in literature, corona discharge was observed prior to full electrical breakdown. This glow persisted throughout the entire operation of the experimental apparatus.

When electrical breakdown occurred, the observable arc extended from only one electrode. This phenomenon was consistent with previous experiments and featured distinct on/off behavior.

Equipment Calibration

The following fit was found between DC output voltage (VDC) and AC input voltage (VAC):

$$VDC = 48.24 \cdot VAC - 1945.2. \quad (1)$$

To obtain the aforementioned fit, DC voltage output was measured for a given AC voltage input. Unfortunately, a high voltage probe was not available, so a traditional multimeter was employed for the task. This equipment was rated for 2000VDC, and so our measurement range was confined by this upper boundary. Further, the transformers were found to spike in output at a certain threshold input, thus defining a lower boundary at approximately 1800VDC. This meant that the possible range of measurements was extremely limited, and thus the fit cannot be said to be very accurate.

The HV power supplies were measured individually and a linear fit was extrapolated from the data. This individual measurement was needed as the linked power supplies produced a compounding effect that made measurement in the 1800-2000VDC range extremely difficult. Note that in the current configuration, the power supplies are linked to double amperage rather than to double voltage, so individual measurement can be justified.

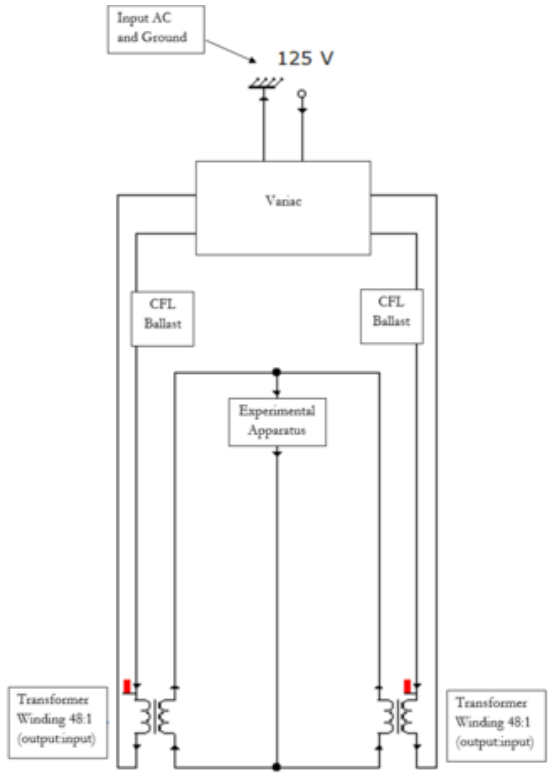

Fig. 2. Wiring diagram for the operating HV power supply

Corona Discharge Voltage Measurements (n=100)

Corona discharge measurements were performed at an absolute pressure of 10kPa and was also observed to display distinct on/off behavior. The data was able to be fitted with a linear model:

$$VDC_{Corona\ Discharge} = 13951\frac{V}{m} \cdot Gap\ Distance\ (m) + 852V. \quad (2)$$

Uncertainties for the current model were also evaluated. The final values for the slope and y-intercept were determined to be $13951 \pm 843\frac{V}{m}$ and $852 \pm 38V$, respectively. Residuals and a chi-squared value of 13.3 were calculated, indicating a less than adequate fit between the linear model and experimental data, which was also seen in the slight upward trend in the residuals plot of figure 10. However, no other model was able to produce a lower chi-squared.

The data in figure 9 show that corona voltage increases as the electrode gap distance increases. This increase ranges just under 2000VDC for a 0.1m increase in electrode gap distance. In figure 9, the calculated standard deviation was seen to be relatively small; this is supported by the fact that corona discharge displayed very distinguishable on/off behavior. However, the spread of the data points at similar electrode distances is large compared to the individual SD's. This contributes to the high chi-squared and suggests that experimental data differed significantly between trials. The source of this variation could be linked to the DIY nature of the current experiment. A slight change in the curvature in the electrodes may influence the true electrode gap, thus yielding different values for corona discharge.

Breakdown Voltage Measurements (n=131)

Clear on/off behavior was observed, but only under certain configurations. Unfortunately, the reverse electrode configuration presented difficulties for the current measurement as the arc was distributed along the circumference of the electrode loop.

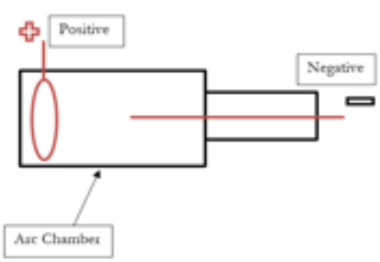

Fig. 3. Reverse electrode configuration

It was thus difficult to distinguish between corona discharge, which is present at voltages lower than the breakdown voltage, and the point of breakdown. Nevertheless, a linear model was found with the parameters $m = 20166 \pm 1332\frac{V}{m}$ and $b = 2064 \pm 58V$:

$$VDC_{Electrical\ Breakdown} = 20166\frac{V}{m} \cdot Gap\ Distance\ (m) + 2064V. \quad (3)$$

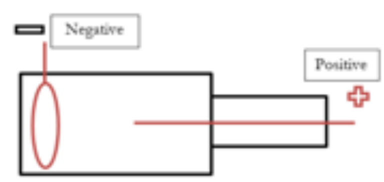

Fig.4. Normal electrode configuration. Arcing occurs between the two electrodes.

The difficulty in data collection yielded a much higher standard deviation than in corona discharge trials, as shown in figure 11. Consequently, chi-squared was quite low, at 0.56. Scattered residuals and the aforementioned chi-squared indicate that the current linear fit is adequate.

Similar to corona discharge voltage, breakdown voltage appears to increase with increasing electrode distance. Variation between data sets is once again demonstrated to be significant. In this case, data-sets demonstrated similar slopes but vastly different Y-intercepts, ranging from 1000 VDC to 3000 VDC. These differences among experimental trials could again be attributed to the low-cost nature of the current project. Unaccounted extraneous variables, such as ambient humidity and temperature, could cause the recorded differences. Further, the output of the power supply may have fluctuated, rendering the initial VAC to VDC fit inaccurate.

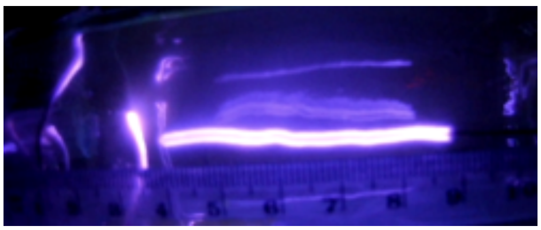

Fig. 7. Corona discharge observed at high vacuums (10kPa). Notice the lack of an arc.

Fig. 8. Observed electrical breakdown between two electrodes.

Breakdown Pressure Measurements (n=105)

Distinct on/off behavior allowed for the precise measurement of required breakdown pressure. No difficulty in distinguishing breakdown pressure was noted. Once again, a linear model was shown to be fitting for the representation of the current data. A fit was calculated with $m = -370\frac{kPa}{m} \pm 10\text{kPa}$ and $b = 42.1 \pm 0.5\text{kPa}$:

$$Pressure_{Electrical\ Breakdown} = -370\frac{kPa}{m} \cdot Gap\ Distance\ (m) + 42.1kPa. \quad (4)$$

Residuals in figure 14 demonstrate a good model fit with points evenly dispersed across the x-axis. However, a chi-squared value of 66 indicates a poor fit between data and model. In this set of experiments, data from trials were dispersed in magnitude – no distinct separation of trials was seen as per the graph of breakdown voltage versus electrode gap distance. Instead, each data set fluctuated significantly around the computed model. This observation could be the result of the relative inaccuracy of the present system. A pressure release valve was manually operated to maintain a given pressure. As such, breakdown pressure could not have been recorded with great accuracy. However, a low standard deviation, as shown on figure 13, suggests that the previous notion is not true.

A decreasing relationship was nevertheless observed in figure 13. As the electrode distance increased, the absolute pressure required for discharge decreased. Across an electrode gap difference of 0.1m, a decrease of up to 40kPa was observed to induce electrical breakdown. Figure 13 seems to be indicative of a logarithmic relationship, but a computed model did not improve the quality of the model fit. Thus, a linear relationship was found to be adequate.

Discussion

In the current experiment, linear fits were found for all voltage and pressure measurements. Phenomena with voltage as a function of electrode gap distance exhibited an increasing trend. Similarly, vacuum needed to sustain an arc increased with increasing gap distance, resulting in the negative correlation between absolute pressure and electrode gap. The obtained models are summarized as follows:

$$VDC_{Corona\ Discharge} = 13951\frac{V}{m} \cdot Gap\ Distance\ (m) + 852V. \quad (5)$$

$$VDC_{Electrical\ Breakdown} = 20166\frac{V}{m} \cdot Gap\ Distance\ (m) + 2064V. \quad (6)$$

$$Pressure_{Electrical\ Breakdown} = -370\frac{kPa}{m} \cdot Gap\ Distance\ (m) + 42.1kPa. \quad (7)$$

Voltage-Distance Analyses

As previously mentioned, corona discharge and electrical breakdown operate by the same mechanism. The key difference between the two phenomena lies in the fact that the air gap between electrodes is partially conductive at the corona voltage and completely conductive at the breakdown voltage (Goldman et al., 1985; Peek, 1929).

A positively correlated trend for voltage phenomena is intuitive when the current model of conduction is considered. At the breakdown electric field, neutral molecules in the air gap between the electrodes are ionized. It is hypothesized that the breakdown electric field is constant regardless of gap distance, as it is known that the unit dielectric strength of air is constant at a constant pressure (Peek, 1929); this hypothesis is in fact supported by an earlier study on this topic (Lisovskiy et al., 2000). The current experimental data aligns with this theory: as electrode gap increases, more potential difference is needed to create the same electric field. Unfortunately, the current experimental apparatus is composed of a conductive loop and a piece of straight wire, and thus does not behave like an ideal plane-plane or sphere-sphere configuration, so the electric field behaves with an unknown distance dependence.

The increasing trend of corona discharge can be explained by an argument similar to the one above. Although corona phenomena result from the ionization of air surrounding an electrode, a certain threshold electric field must be present to induce this conductivity.

Comparison of the discharge and corona models yields an observable difference in slopes and y-intercepts. In both cases, the breakdown voltage model exhibits a greater value than the corona voltage plot. A t-score of 4 was calculated between the slopes of the models and a score of 17 for the y-intercepts, suggesting that both parameters are statistically different.

As corona discharge does not require complete conduction in air, it is presumed that less potential, and thus less electric field, is required to produce these effects (Goldman et al., 1985). This theory would explain the larger potentials needed to induce electrical breakdown, and is consistent with previous descriptions of corona discharge as a pre-cursor to dielectric breakdown (Peek, 1929).

The difference in slopes reveal that the voltage required for electrical breakdown increases at a greater rate than that for corona discharge. However, previous characterization of these phenomena does not fully support this finding. Although a t-score of four is often enough to distinguish the difference between two values, the relatively low t-score could suggest that the two slope values are in tension. As such, no conclusive comparison can be established with current data.

Pressure-Distance Analysis

In the given model, there exists a negative correlation between pressure and gap length. Pressures above the breakdown pressure would contain a too-high density of air for dielectric breakdown. Ionization of air in the gap would thus be not possible, and no spark was created. This is supported by the positively correlated linear behavior of dielectric strength with increasing absolute pressure, as established by Peek in 1929. So, higher absolute pressure results in higher dielectric strength, thus requiring shorter electrode distances for an arc to occur at the same input voltage.

Comparison of Electrode Configurations

The current data suggests that electrode configuration is not a factor in electrical breakdown. Average t-scores were calculated to be 0.54, 0.56, and 0.28 between data for the different electrode configurations.

Comparison to Literature

The currently accepted model for electrical breakdown in a vacuum is mathematically described by Paschen's law (Berzak et al., 2006; Wang, 2013; Massarczyk et al., 2016; Peek, 1929):

$$V_{breakdown} = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]} . \quad (8)$$

$V_{breakdown}$ represents the voltage required for discharge to occur. P and d signify the pressure in kilopascals and electrode gap in centimeters, respectively. A and B are experimentally determined constants with units $(kPa \times cm)^{-1}$.

Previous analyses were conducted with breakdown voltage as the y-axis and the product of pressure and electrode gap distance as the x-axis, as displayed in figure 15 (Al-Hakary et al., 2014; Berzak et al., 2006).

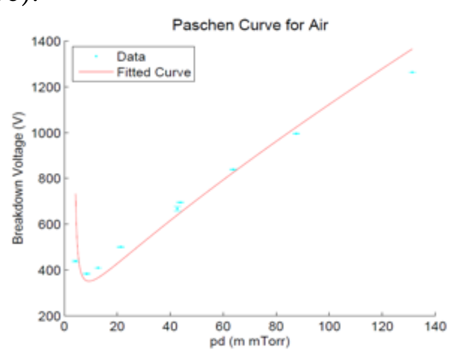

Figure 15. Experimental Paschen's curve for air. Taken without permission from Berzak et al., 2006.

In the present study, a linear correlation is expected as either pressure or electrode gap distance increases. This is because the non-linear dip in breakdown voltage seen in figure 15 is far below the operating conditions of the current experiment. This supports our current findings – breakdown voltage increases linearly with increasing electrode gap distance and increasing pressure.

It must be noted that the great majority of experiments conducted to verify Paschen's law were operated in much lower pressures than those used in the present study. In the experiment that produced figure 15, the pressures used were on the 10-1kPa magnitude (Berzak et al., 2006). The current experiment explored pressures in the 101kPa magnitude. To explore whether breakdown voltage at higher pressures, and thus higher pressure-distance x-values, is consistent with Paschen's law, our current model was plotted with other available experimental data in figure 16 and 17.

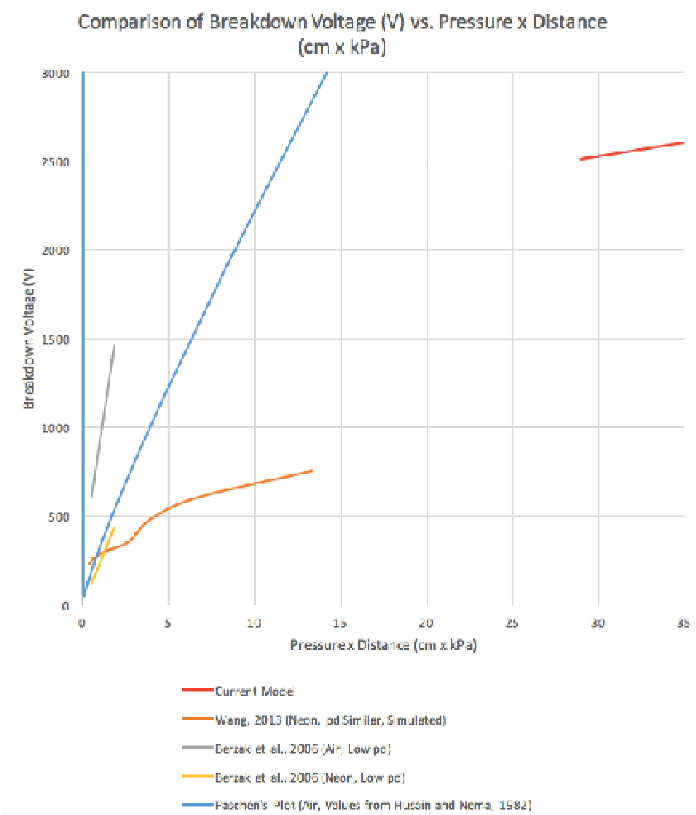

Fig. 16. Comparison of current model with literature data and mathematical models in their respective pressure-distance ranges. Model fits were calculated from raw data taken without permission from the mentioned research papers.

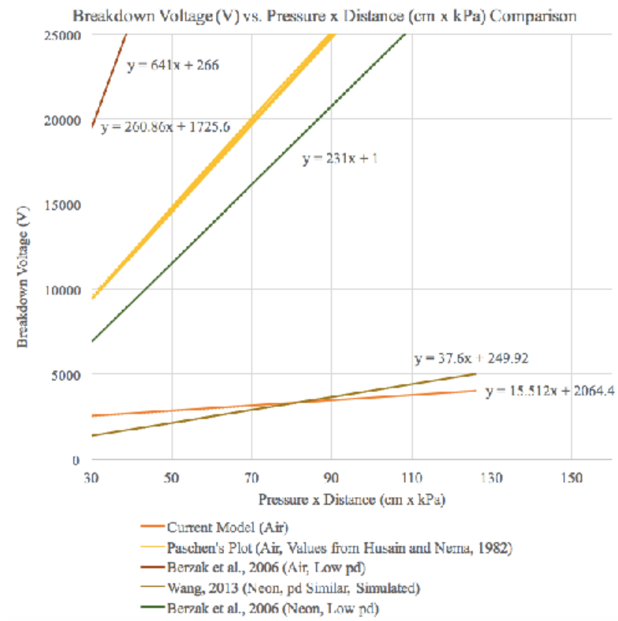

Fig. 17. Comparison of current model with literature data and mathematical models with extrapolated slopes for direct comparison. Model fits were calculated from raw data taken without permission from the mentioned research papers.

From the figures, it is clear that there exists immense variation in current experimental data. Specifically, experiments involving low pressure-distance configurations were modeled by slopes much greater than the present fit. A calculated chi-squared between the Paschen's law model and our current data yielded a value on the order of 1017 magnitude, indicating an obvious difference between the two fits. Previous experiments with similar experimental conditions as the current experiment, however, were able to produce plots on or near the same order of magnitude as our current data, but unfortunately did not involve air as a conductive medium (Wang, 2013; Massarczyk et al., 2016).

To create a point of reference, data for neon and air environments were taken from Berzak et al.'s 2006 study of Paschen's law. In their study, low pressure-distance configurations were used, on the 10-1kPa magnitude as previously mentioned. The slopes of both plots lie in the same order of magnitude as a mathematically calculated plot of Paschen's law, but are significantly greater than that produced by the current study. Wang's 2013 simulation in neon, on the other hand, involved conditions more similar to the present experiment and produced a plot on the same order of magnitude as our current model. This comparison suggests that voltage versus pressure-distance behavior assumes a lower slope for higher pressure-distance values, and that Paschen's law is inadequate for describing higher pressure-distance configurations.

Given the DIY nature of the current experiment, however, this finding is not conclusive. Thus, there are two possible explanations for the gathered data. First, the DIY experimental apparatus and measuring techniques employed in the current experiment was insufficient in gathering accurate data. Second, the current Paschen's model breaks down at the pressure distance values tested in the current study.

Conclusion

In the current experiment, an experimental apparatus was built to observe and record the nature of high voltage phenomena in a near-vacuum. Three main classes of measurements were conducted: corona discharge voltage, electrical breakdown voltage, and electrical breakdown pressure. The gathered data was fitted to find a linear relationship between the phenomena voltage and electrode gap length:

$$VDC_{Corona\ Discharge} = 13951\frac{V}{m} \cdot Gap\ Distance\ (m) + 852V. \quad (9)$$

$$VDC_{Electrical\ Breakdown} = 20166\frac{V}{m} \cdot Gap\ Distance\ (m) + 2064V. \quad (10)$$

The absolute pressure needed for arcing to occur was found to decrease linearly with increasing electrode gap length:

$$Pressure_{Electrical\ Breakdown} = -370\frac{kPa}{m} \cdot Gap\ Distance\ (m) + 42.1kPa. \quad (11)$$

Previous experimental models were not found for corona discharge voltage and electrical breakdown pressure requirements. However, an established model, Paschen's law, was available to predict the breakdown voltage of a given configuration as a function of pressure times distance. The current experimental model was compared to the mathematical model as well as available research on the topic. It was found that the current DIY apparatus could be insufficient in yielding viable data. However, the current findings also reveal the possibility that Paschen's law is not adequate in predicting electrical breakdown voltage at higher pressure-distance configurations.

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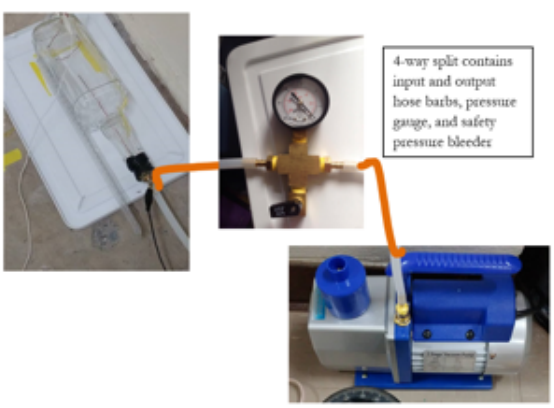

Fig. 5. Airflow apparatus for the present experiment

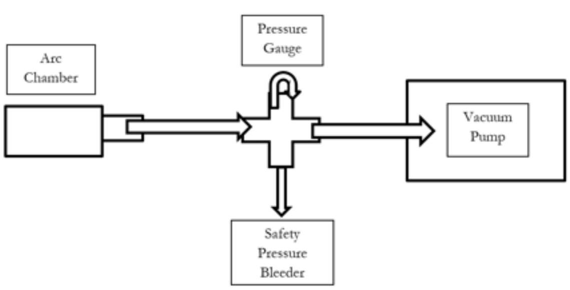

Fig. 6. Airflow diagram

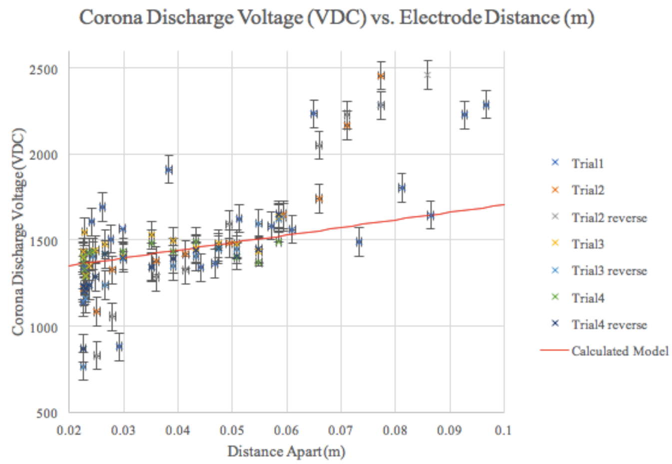

Fig. 9. Corona voltage data with fitted model. Uncertainties calculated from SD.

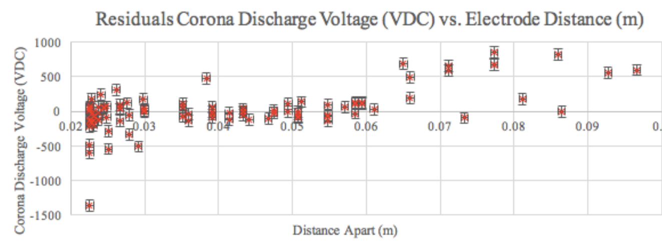

Fig. 10. Residuals of the calculated model. Notice the lack of a clear trend and the even distribution of data points around the x-axis.

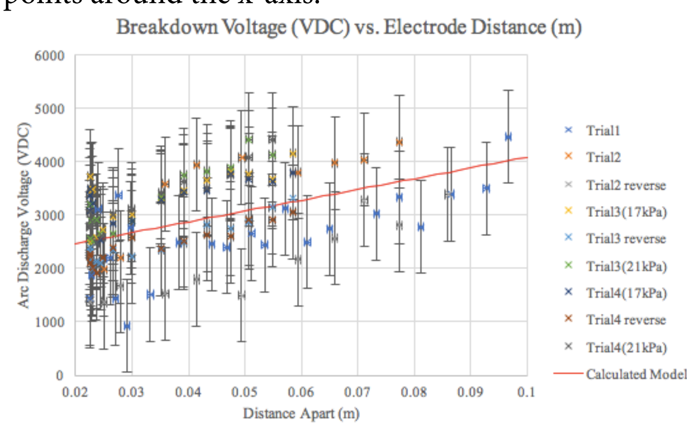

Fig. 11. Collected data with fitted model breakdown voltage (VDC) vs. electrode gap distance (m). Uncertainties calculated from SD.

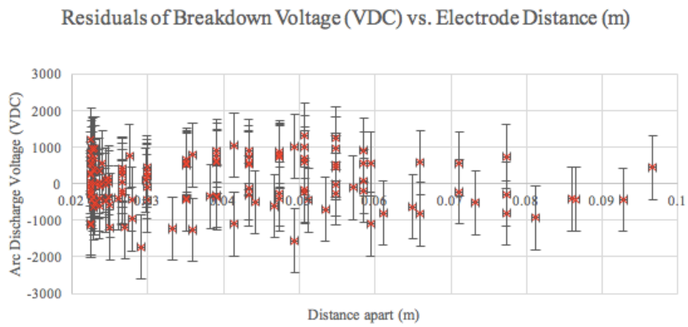

Fig. 12. Residuals plot for the electrical breakdown linear model.

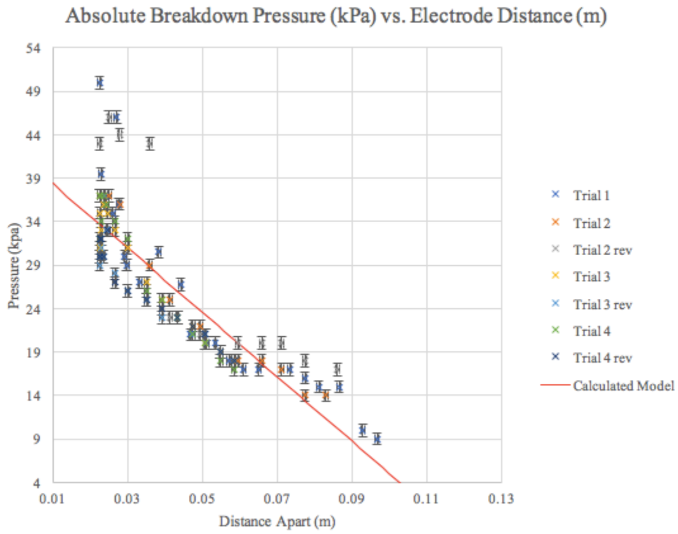

Fig. 13. Breakdown pressure (kPa) vs. electrode gap distance (m) data with plotted model. Uncertainties calculated from SD.

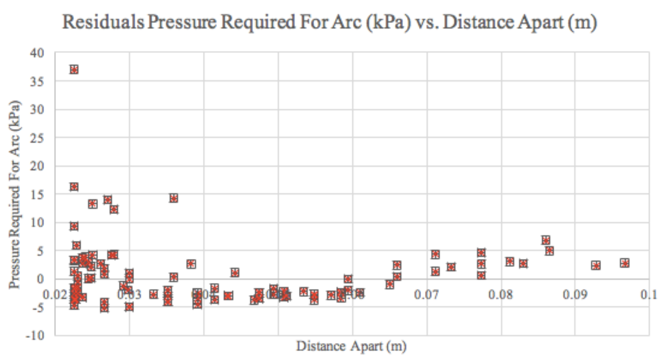

Figure 14. Residuals for the current model.

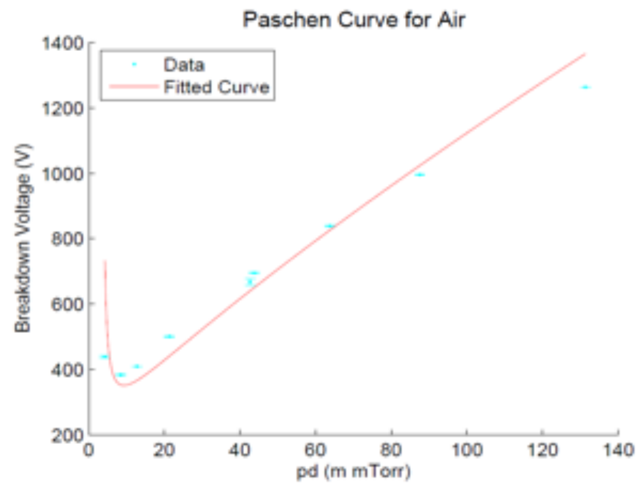

Figure 15. Experimental Paschen's curve for air. Taken without permission from Berzak et al., 2006.