OBJECTIVES

1. Measure the breakdown voltages $U_{br}$ at varying electrode gap distances $d$ under a fixed pressure $p$ of air.

2. Plot and compare the Paschen curves using the raw data at different pressures.

3. Compute the value of the second Townsend coefficient $\gamma$.

INTRODUCTION

In a gas system between two electrodes, an application of an electric field of strength $E$ can cause an electric discharge, i.e. a sudden presence of electric current in the system. The discharge is self-sustaining when each charge carrier in the gas, within its lifetime before being neutralized, can generate at least one more charge carrier in the course of motion in the system. This is also known as the point of electrical breakdown. Common sources of electric discharge include ambient radioactive irradiation as well as short-wavelength electromagnetic radiation which can cause ionizations of neutral atoms to form electrons and positive ions. If these processes are self-sustaining, the gas becomes permanently ionized (plasma).

The origin of electric currents in a gas comes from the electrons and positive ions produced during ionization of neutral gas atoms, which move under an external electric field. Such a field gives the charge carriers a drift velocity so that a uniform current can persist between the two electrodes. Since the electrons are lighter in mass compared to the ions, they have much larger average kinetic energies and are mainly responsible for ionization of atoms. Under the electric field, the electrons drift toward the anode (+ electrode) and the ions drift toward the cathode (- electrode).

There are two important processes in the gas system which give rise to electrical breakdown.

**Ionization**: If the energy of an incoming electron is larger than the ionization energy of an electron in a gas molecule, that electron will be imparted with an energy that separates itself from the molecule, forming a positive molecular ion.

**Secondary electron generation**: If the energy released from the recombination of a positive ion and an electron from the cathode exceeds the work function of an electron in the conduction band of the cathode, which is defined as the energy difference between the vacuum and the electron band, then this electron will be ionized out of the cathode. Such a process is known as the Auger effect. Thus electrical breakdown occurs once this condition is met since now, additional charge carriers are generated.

In this experiment, we perform a simple investigation on the electrical breakdown of a system of air molecules between two parallel electrode plates of distance $d$ between them. The current is kept low so that the temperature is below the critical value beyond which thermionic emission occurs. The electric field is also not too strong in order to avoid field emission of excess free electrons from the electrodes. The parallel electrode plates are used to avoid corona discharge due to accumulation of charges on cornered surfaces that can cause high potential gradients around them.

In Townsend's theory of electrical breakdown, we introduce the coefficient $\alpha$, known as the first Townsend coefficient, which refers to the rate of ionization events per unit length for electrons having a drift velocity in
the direction of the electric field $E$. The number of electrons ($N_e$) and ions ($N_i$) due to the electron avalanche process starting from a distance $x$ away from the cathode are given by

$$N_e = e^{ax}, \quad N_i = e^{ax} - 1$$  \hspace{1cm} (1)$$
since at $x = 0$, no ions are produced as there is no room for the electron avalanche process. Introducing the second Townsend coefficient $\gamma$, which is the probability of an ion generating one secondary electron from the cathode that is in general dependent on the gas, electrode material and surface condition, the maximal number of secondary electrons generated from the maximal number of positive ions produced from an avalanche starting from the full distance $d$ away from the cathode is simply

$$N_{e,sec} = \gamma(e^{ad} - 1)$$  \hspace{1cm} (2)$$
Reminding ourselves that the electrical breakdown will occur as long as after an electron avalanche, there is one (or more) additional secondary electron generated to sustain the discharge, we arrive at the following Townsend breakdown criterion

$$\gamma(e^{ad} - 1) = 1$$  \hspace{1cm} (3)$$
by simply setting $N_{e,sec}$ to one. In a realistic situation, the gas may be electronegative and one should choose a smaller $\gamma$ coefficient than that for the neutral gas to account for the presence of negative ions which is not due to electrical breakdown.

It was shown that the fraction $\frac{\xi}{p}$ is a function $\xi(\frac{E}{p})$ of $\frac{E}{p}$. If the gas is purely nitrogen, then experiments [2, 3] have shown that $\xi(\frac{E}{p})$ takes on the form

$$\xi(\frac{E}{p}) = A e^{-B \frac{E}{p}}$$  \hspace{1cm} (4)$$
where $p$ is the pressure of the gas and $A$ and $B$ are gas-specific constants. Table 1 shows some values for different gases. One has to note that Eq. (4) is an approximation that is valid with $\frac{E}{p}$ below the value of about 1140 V/(Pa m), which is within the limits of our experiment. We shall assume that Eq. (4) is reasonably accurate for air, which will be the gas that we are using, since 78% of it is nitrogen. However, results can still vary significantly depending on the type of gas used, especially when contaminants are present in the gas.

<table>
<thead>
<tr>
<th>Gas</th>
<th>$A/ (\text{Pa} \cdot \text{m})^{-1}$</th>
<th>$B/ (\text{Pa} \cdot \text{m})^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>20</td>
<td>487</td>
</tr>
<tr>
<td>CO2</td>
<td>27</td>
<td>621</td>
</tr>
<tr>
<td>H2</td>
<td>7</td>
<td>173</td>
</tr>
<tr>
<td>N2</td>
<td>13</td>
<td>413</td>
</tr>
<tr>
<td>He</td>
<td>4</td>
<td>45</td>
</tr>
<tr>
<td>Ar</td>
<td>16</td>
<td>240</td>
</tr>
</tbody>
</table>

**Table 1:** The constants $A$ and $B$ for different types of gases.

Since the electric field is constant in this setup, with the strength being $U_{br}/d$ and $U_{br}$ referring to the breakdown voltage, we have

$$d = \frac{e^{Bpd/U_{br}}}{pA} \ln \left(\frac{1}{\gamma} + 1\right)$$  \hspace{1cm} (5)$$
and together with Eq. (4),

\[
U_{br} = \frac{kpd}{\ln\left(\frac{Apd}{\ln(\gamma+1)}\right)}.
\]  

(6)

\(U_{br}\) is known as the Paschen function and has a minimum value \(U_{min}\), along with other minimum quantities, given by

\[
U_{min} = 2.71828 \frac{B}{A} \ln \left(\frac{1}{\gamma} + 1\right),
\]  

(7)

\[
\left(\frac{E}{p}\right)_{min} = B,
\]  

(8)

and

\[
(pd)_{min} = 2.71828 \frac{1}{A} \ln \left(\frac{1}{\gamma} + 1\right).
\]  

(9)

Typical graphs of \(U_{br}\) look like those in Fig. 1.

**Fig. 1:** Typical Paschen curves for different pressure values \(p\).
EXPERIMENTAL PROCEDURES

1. Set the equipment up as shown in Fig 2.

Fig. 2: Experimental setup. Clockwise from right: (a) vacuum pump, (b) plasma physics experimental set, (c) pressure meter, (d) plasma physics operating unit (e) digital multimeter with peak-hold function and (f) fine pressure control valve.

2. Pay regard to the operating instructions of the vacuum pump and the Plasma Physics Operating Unit.

3. Use only safety connecting cables to connect the digital multimeter to the Plasma Physics Experimental Set. Select the 1000 V DC range of the multimeter.

4. Close the fine control valve and switch on the vacuum pump.

5. Adjust the pressure $p$ in the chamber to the desired value by gently opening the fine control valve.

6. With the Plasma Physics Operating Unit switched ‘OFF’, set the micrometer screw to zero and ensure the distance between the two electrodes is also zero by gently pushing in the micrometer rod.

7. Increase the electrode distance $d$, e.g. to 0.2 mm, and switch ‘ON’ the Plasma Physics Operating Unit.

8. Set the operating mode switch on the Plasma Physics Operating Unit to “cont.” and the voltage adjustor to maximal voltage.

9. Vary the electrode distance $d$ with the micrometer screw to find out the minimal distance where the glow discharge can ignite with the given maximal voltage. When adjusting the micrometer screw, avoid the danger of overwinding it (not <0 mm and not >6 mm).

10. Lower the voltage setting again and adjust $d$ to a value wider than the minimal possible distance for this pressure.

11. Activate the peak hold function of the digital multimeter and slowly increase the voltage until electrical breakdown occurs and a glow discharge appears. This will increase the current between the electrodes and decrease the electrode voltage at given voltage adjustor setting.

12. Turn the voltage adjustor down again until glow discharge disappears.
13. Note down the multimeter reading as breakdown voltage $U_{br}$.

14. Release and re-activate again the peak hold function of the digital multimeter.

15. Repeat measurement three times for each electrode distance, average the voltage values.

16. Table 2 shows a possible measurement protocol.

17. Increase electrode distance $d$ while keeping pressure $p$ constant, note down next breakdown voltages.

18. At relatively high pressures (above 5 hPa) the voltage increase has to be slower than 1 V/s near the breakdown voltage in order to obtain correct values since it may take some time until sufficient initial ionization appears statistically to start the breakdown.

19. Measure the dependence of breakdown voltage $U_{br}$ on electrode distance $d$ at 2 hPa, 4 hPa and 6 hPa.

20. Plot the breakdown voltage $U_{br}$ at different pressure values over $d$ using the data.

21. Plot the breakdown voltage $U_{br}$ at different pressure values over $pd$ using the data and comment on the result.

22. Compute the second Townsend coefficient $\gamma$.

23. At the end of the experiment, set the Plasma Physics Operating Unit voltage control knob to zero and its mains switch to the ‘O’ position (off).

24. Before switching off the vacuum pump, open the fine control valve so as to minimize back-flow of oil/vapour into the chamber.

<table>
<thead>
<tr>
<th>$d$ / mm</th>
<th>$U_{br}^{(1)}$ / V</th>
<th>$U_{br}^{(2)}$ / V</th>
<th>$U_{br}^{(3)}$ / V</th>
<th>$U_{br}^{avg}$ / V</th>
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<tbody>
<tr>
<td>0.20</td>
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<td>0.30</td>
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<td>5.00</td>
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Table 2: Sample table for tabulating measured results for a given value of $p$. 
QUESTIONS

1. Explain the shape of a particular Paschen curve and the existence of the minimum point. (Hint: Recall the origin of an electric discharge as well as the basic relations between a constant electric field and its electric potential.)

2. Explain the observed shift in the minimum point as the pressure changes.

3. Name and describe briefly one application of the Townsend discharge process.

BIBLIOGRAPHY


**TIPS**

1. For every distance $d$, turn the “Voltage” knob at moderate speed to approximately locate the breakdown voltage; take this reading as a gauge. Subsequently, turn the knob at moderate speed to about 30 V below the approximate reading and wait for about 40 seconds before turning it at a much slower pace to the actual breakdown voltage.

2. When the surfaces of the electrodes (fixed and variable) are dirtied, extreme variations in the individual measured values for a fixed $d$ are observed. To remove the contamination, the front faces of the electrodes can be cleaned with alcohol.

3. It will be a good idea to furnish linear plots from Eq. (6) in order to check the accuracy of the measured data. An example will be to plot $d/U_{br}$ against $\ln(d)$ to see if the measured data give straight lines.

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