Breakdown Initiation and Electrical Strength of a Vacuum Insulating System in the Environment of Selected Noble Gases at AC Voltage

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Abstract: This paper presents the results of testing the electrical strength of an insulating system in a vacuum obtained from three noble gases: argon, neon, helium, and air. The breakdown voltages were measured for contact gaps of 1 mm and 2 mm. A difference was observed in the pressure range where the electrical strength was kept constant. The chamber filled with helium residual gases lost its insulating properties at the highest pressure among the tested gases (2.00 × 10^0 Pa at contact gap \( d = 2 \) mm), while the chamber filled with argon gas lost its insulating properties at the lowest pressure among the tested gases (2.00 × 10^-1 Pa at contact gap \( d = 2 \) mm). After a decrease in electrical strength, an intense glow discharge was observed. A theoretical description related to the initiation of an electrical breakdown in vacuum insulating systems is also presented. The situation in which the discharge chamber with a contact system was filled with the mentioned gases was analyzed. The mean free paths of the electrons and molecules as well as the velocities and energies of the electrons accelerated by the voltage applied to electrodes were calculated. The obtained results were related to the measurement parameters and analyzed in terms of the discharge development. The results of the research suggest alternatives for the further development of vacuum-extinguishing chambers used in environmentally-friendly electrical switchgear by increasing the rated operating pressure, maintaining the required electrical strength values, and thus facilitating the operation due to greater certainty in regard to maintaining the integrity of such a vacuum interrupter.

Keywords: noble gases; electrical strength; electrical breakdown initiation; glow discharges

1. Introduction

1.1. Current Research Directions Related to Low Pressure Gas Discharges

In recent decades, there has been considerable interest in the use of vacuum technology as an insulating medium in power switchgear. Despite many scientific studies, the physical aspects of discharges in vacuum insulation systems are still of interest to researchers worldwide.

Most of the available scientific work related to low-pressure gas discharges relates to studies carried out using direct voltage (DC)-powered stations \([1–5]\), as well as combinations of direct and alternating voltage (AC) systems \([6,7]\). This work is primarily concerned with the measurement of breakdown voltages in environments of different types of gases, with different configurations of the contact systems, with an emphasis on the physical aspects of the observed and measured phenomena.

However, the scientific works cited above cover the pressure range, including the right and left branches of the Paschen curves along with the so-called “well” of these curves. The authors of this paper have focused on lower pressure values (higher vacuum) at which the electric strength reaches a constant value and the strength curve flattens out. At such pressure values, the probability of the development of electron avalanches at the initiation of an electrical breakdown is significantly reduced.
The research carried out by the authors was conducted with a view to industrial applications in vacuum switchgear, and therefore the test rig was powered by an alternating test voltage (AC) with a mains frequency of 50 Hz, which is new compared to the abovementioned works.

In terms of industrial applications, recent publications in the scientific area under review are mainly concerned with insulating alternatives to harmful sulfur hexafluoride (SF$_6$) and the detailed analysis of electric arc burning processes in vacuum [8–12]. In addition to the commonly produced extinguishing chambers based on vacuum or sulfur hexafluoride, mixtures of SF$_6$ gas with nitrogen, in the ratio of 40% SF$_6$ and 60% N$_2$, are currently encountered. The projected direction of research on the application of electro-insulation gases in vacuum interrupters mainly involve mixtures of sulfur hexafluoride with helium, argon, nitrogen, tetrafluoromethane (CF$_4$), or hexafluoroethane (C$_2$F$_6$) [13]. Both sulfur hexafluoride and the aforementioned perfluorocarbons increase their temperature while residing in the atmosphere and thus create a greenhouse effect. This is evidenced, among others, by the GWP index (greenhouse effect potential), which is 22,200 for SF$_6$, 5700 for CF$_4$, and 9200 for C$_2$F$_6$ [14].

The idea of using a vacuum as an insulating medium is to take advantage of the fact that when the gas pressure is reduced to a value at which the average free paths of molecules and electrons are greater than the contact gap in the insulating system, the development of electron avalanches that initiate discharges in gases is impossible [15].

1.2. Analysis of Discharge Development in the Environment of Selected Noble Gases

The value of the mean free path of molecules in a gas can be calculated using the following relationship [15]:

$$L_m = 3.11 \cdot 10^{-24} \frac{T}{p d_m^2}$$

(1)

where: $T$—absolute temperature of gas (K), $p$—pressure of gas (Pa), $d_m$—diameter of gas molecule (m).

The average free path of electrons in the considered gas can be determined in a similar way [15]:

$$L_e = 1.76 \cdot 10^{-23} \frac{T}{p d_e^2}$$

(2)

Using the above relationships, the average free paths of $L_m$ molecules and $L_e$ electrons in the gases used in this study (air, helium, neon, argon) were calculated. The temperature $T = 293$ K was assumed for the calculations. The characteristics of $L_m$ and $L_e$ as a function of the pressure of the selected gas are shown in Figure 1a–d. The values of the mean free paths were calculated for gas pressures $p$ ranging from $10^{-5}$ Pa to $10^{5}$ Pa.

On the basis of Equations (1) and (2) and the following figures it can be stated that the larger the diameter of the molecule of the studied gas, the smaller the value of the average free path of electrons and molecules at a given gas pressure. Among the noble gases analyzed, helium has the smallest particle diameter, while argon has the largest [16]. Therefore, at the selected pressure value, electrons and helium molecules will travel the longest distance between subsequent collisions, in contrast to argon, where the distance travelled by electrons and molecules between subsequent collisions will be the shortest among the noble gases analyzed.
However, it is crucial to determine the pressure value at which the mean free path is equal to the contact gap value set in the study. Figure 2a–d show the calculated values of the mean free paths of molecules $L_m$ and electrons $L_e$, which are equal to the values of the contact gaps $d$ at the selected pressure value $p$. The calculations were performed based on the following relationships:

$$p_1 = \frac{3.11 \times 10^{-24} \cdot T}{L_m \cdot d_m^2}$$  \hspace{1cm} (3)$$

$$p_2 = \frac{1.76 \times 10^{-23} \cdot T}{L_e \cdot d_m^2}$$  \hspace{1cm} (4)$$

where the values of the mean free paths of $L_m$ molecules and $L_e$ electrons were substituted for the selected contact gaps $d$. 

Figure 1. Dependence of mean free paths of molecules and electrons as a function of pressure of selected gases: (a) air, (b) helium, (c) neon, (d) argon.
Figure 2. Characteristics to determine the value of pressure $p$ at which the mean free paths of molecules $L_m$ and electrons $L_e$ are equal to the contact gap $d$ in the environment of selected gases: (a) air, (b) helium, (c) neon, (d) argon.

At values below the pressure $p$ values read from the curves for a given contact gap $d$ equal to the mean free path $L_m$ and $L_e$, the probability of avalanches developing and initiating a breakdown in a vacuum environment with residual gases in the form of air, helium, argon or neon decreases until it becomes impossible. In this situation, each particle and each electron will travel the contact gap without colliding.

This paper presents the results of electrical strength tests at varying residual gas pressures for two contact gaps $d = 1$ mm and $d = 2$ mm, for which the limiting pressure was calculated, below which the development of avalanches initiating the breakdown is impossible. These values are summarized in Table 1.
Table 1. Summary of pressure values at which the mean free paths of electrons and molecules equal the contact gap tested.

| Residual Gas Type | \( d = 1 \text{ mm} \) | \( d = 2 \text{ mm} \) |
|-------------------|-------------------|-------------------|
|                   | \( P_{(d=Lm)} \)  | \( P_{(d=Lc)} \)  |
|                   | \( P_{(d=Lm)} \)  | \( P_{(d=Lc)} \)  |
| Air               | \( 6.66 \times 10^0 \text{ Pa} \) | \( 3.77 \times 10^1 \text{ Pa} \) | \( 3.33 \times 10^0 \text{ Pa} \) | \( 1.88 \times 10^1 \text{ Pa} \) |
| Helium            | \( 1.88 \times 10^1 \text{ Pa} \) | \( 1.07 \times 10^2 \text{ Pa} \) | \( 9.41 \times 10^0 \text{ Pa} \) | \( 5.33 \times 10^1 \text{ Pa} \) |
| Argon             | \( 6.69 \times 10^0 \text{ Pa} \) | \( 3.79 \times 10^1 \text{ Pa} \) | \( 3.35 \times 10^0 \text{ Pa} \) | \( 1.89 \times 10^1 \text{ Pa} \) |
| Neon              | \( 1.40 \times 10^1 \text{ Pa} \) | \( 7.93 \times 10^1 \text{ Pa} \) | \( 7.01 \times 10^0 \text{ Pa} \) | \( 3.97 \times 10^1 \text{ Pa} \) |

The change in the mechanisms of initiation and development of discharges in the studied gases occur at the highest values of pressure in the case of helium, while in the case of argon they occur at the lowest. This is also due, as in the case of mean free paths, to the geometric dimensions of the molecules of the selected gas.

In a vacuum environment, where collisions between electrons do not occur, it is possible to calculate the kinetic energy of an electron that has traveled without collisions between electrodes to which a voltage of \( U \) has been applied [15]:

\[
E_{ke} = \frac{1}{2} m_e v_e^2 = eU \tag{5}
\]

where: \( m_e \)—rest mass of the electron (kg), \( v_e \)—terminal velocity of the electron (m/s), \( e \)—charge of the electron (C).

From the above relationship, the velocity of the electron in the free state can be determined:

\[
v_e = \sqrt{\frac{2eU}{m_e}} = 5.93 \times 10^5 \sqrt{U} \tag{6}
\]

On the basis of Equations (5) and (6), the dependence of the kinetic energy of the electron and its velocity as a function of the voltage applied to the electrodes was plotted. The obtained characteristics are shown in Figures 3 and 4.

![Figure 3](image-url)  
Figure 3. The dependence of: (a) electron kinetic energy \( E_{ke} \) and (b) electron velocity \( v_e \) as a function of voltage \( U \) applied to the electrodes.
The values of the electron kinetic energy $E_{ke}$ and its velocity $v_e$ were calculated for a voltage range $U$ in the range $10^3 \div 10^5$ kV. The higher the supply voltage, the higher the velocity and kinetic energy of the electron will be. For example, when a voltage of 20 kV is applied to the test system, in a vacuum insulating system, where the electron will travel through a contact gap $d$ without collisions, it will acquire a kinetic energy equal to $E_{ke} = 3.20 \times 10^{-15}$ J and a velocity equal to $v_e = 8.39 \times 10^7$ m/s.

When the pressure values are below those summarized in Table 1, the initiation and development of the discharge between the electrodes are made possible by physical phenomena other than those responsible for the breakdown above the summarized values. Over the years, scholars working on the subject of discharges in vacuum media have developed many hypotheses of the mechanism of initiation and development of discharges in systems of this type.

### 1.3. Initiation of an Electrical Discharge in a Vacuum at AC Voltage

When considering the processes of breakdown initiation in vacuum insulating systems at AC voltage, two variants of the conducted measurements should be considered [17].

In the first case, the rate of voltage buildup is of such a high value that field desorption of gases from the electrodes takes place, and thus conditions will occur in the system that initiate a breakdown by the desorption mechanism. In this situation, the discharge develops in dilute gases from the field desorption process from the surface of the electrodes. This discharge results in a further desorption process and melting and evaporation of the electrode material. The end result is the occurrence of breakdowns, as a result of which the electrodes suffer mechanical damage through the generation of micro-arrows with values greater than 1 µm. The micro-roughness of such dimensions emits electron beams, so that breakdown initiation occurs via field emission [18–20].

In the second case, the voltage buildup rate is characterized by such a small value that the pumping system is able to remove the desorbed gases from the interstitial space. Consequently, the development of a discharge in these residual gases will not be possible due to their insufficient quantity. Over time, as a result of field desorption and electron and ion bombardment, the electrode surfaces will be stripped of most of the adsorbed gases. At this stage, there are micro-discharges in the system [21], which will decrease with the gradual cleaning of the electrodes. In such a case, due to the very small values of the micro-caustics present on the electrode surfaces, the field emission electron current is practically unmeasurable. The situation changes when the system voltage is raised further, because the field emission electron current suddenly appears in the system, which exceeds the sensitivity of the measuring system. When the voltage is lowered and then increased, this current also decreases and then increases gradually in a measurable manner.

When comparing electrical breakdown initiation at DC voltage and AC voltage, it is important to note the transfer of microparticles between the electrodes to which the voltage is applied. In the case of DC voltage, the microparticles mainly come from the anode area, so the direction of electrode material transfer occurs from the anode to the cathode. This shows that the temperature of the anode area bombarded by electrons emitted from the cathode is much higher than the temperature of the tips of the electron-emitting microparticles. The electrostatic forces in this case act equally on each electrode.

In the case of AC voltage with frequencies of 50 Hz and 60 Hz, the breakdown voltage reaches higher values compared to DC voltage [22]. In the case of AC voltage, where the voltage varies cyclically, material transfer occurs in both directions from one electrode to the other. Thus, the electrode surfaces undergo more distortion than in the case of DC voltage. With this type of insulating system, there is an additional factor associated with mechanical stress by the periodically varying electrostatic force. This stress, which is equal to the electrostatic pressure, is determined by the formula [15]:

$$
\sigma(t) = \frac{1}{2} \varepsilon_0 \beta^2 U_m^2 d^{-2} \sin^2 \omega t
$$

(7)
where $\varepsilon_0$—electrical permeability of vacuum, $\beta$—coefficient of amplification of the electric field strength at the surface of the electrode material, $U_m$—voltage amplitude at the terminals of the insulating system, $d$—contact gap, $\omega$—voltage pulsation, $t$—time.

Thus, this force is a pulse cycle with a frequency equal to twice the frequency of the voltage supplying the system. This causes fatigue in the material, so that the mechanical strength is reduced to a value called the long-term fatigue strength. The highest electric field strength, and thus mechanical stress occurs near the tips of the microblades located on the electrode surfaces. The cyclic heating and cooling of the micro-cutting edge reduces the mechanical strength of its material, and in some cases, it drops well below the long-term fatigue strength. Despite this, some microblades continue to emit electrons in a stable manner, and thus their mechanical strength is higher than that reported in the material tables. This paradox can be explained by the fact that the effective field of an electron beam-emitting microblade can range from about $10^{-17}$ to $10^{-15}$ m$^2$ (about 100 to about 10,000 metal atoms arranged side by side). Since the concentration of defects in metals is low, there is a high probability that the microblade-tip material does not have a defect. These types of microblades are stable electron emitters, unlike micro blades that have defects. These microblades can be detached by electrostatic forces and become charged microparticles moving toward an electrode of opposite polarity.

On the basis of research conducted over the last few decades, a model for the initiation of a breakdown at AC mains frequency has emerged, which states that with slow voltage build-up, the electrode surfaces are freed from most of the adsorbed gases. Nevertheless, due to the continuous removal of desorbed gases by the pumping system, the development of a discharge is not possible. In addition to the occurrence of gas desorption from the electrodes, a periodically varying electrostatic force acts on the electrode surfaces, causing mechanical fatigue of the stressed material accompanied by thermal fatigue. Over time, fatigue scrap occurs, which when detached from the electrode, becomes a charged microparticle moving in an accelerated motion towards the opposite electrode. If the microparticle acquires sufficient kinetic energy, it will strike the electrode and produce a crater on its surface. The significant height and sharp edges of the produced crater are good electron emitters, so that the field emission electron current increases in the system. In the meantime, more craters may form on the electrode and thus cause a further increase in current. When the amplitude of this current exceeds a certain value, the limiting temperature in the anode region is also exceeded and the discharge develops according to the anode mechanism [23–25].

After analyzing the presented breakdown initiation mechanism, it can be concluded that the increase in the electrical strength of the vacuum insulating system at AC voltage is possible by reducing the field emission electron current in the system. This can be done by preventing the formation of micro-sharpeners on the electrode surfaces, using thin coatings to suppress the field emission of electrons from the electrode surfaces, and performing conditioning processes [26–28].

2. Research Stands, Materials and Methods

To perform the targeted electrical strength tests, a proprietary laboratory bench was used, consisting primarily of a discharge chamber inside which a contact array is located (Figure 4). The structure of the electrode array was designed and manufactured in an interchangeable manner so that it was possible to change the contacts in order to test the electrical strength with different materials and electrode shapes. The test stand was also equipped with sight glasses so that the person carrying out the test has a direct view of the arc processes taking place in the discharge chamber. The system is also equipped with a special mechanism, which allows the adjustment of the contact gap, as well as switching operations through the use of a switch electromagnetic actuator operated by a dedicated controller.
In the meantime, more craters may form on the electrode and thus ... part, orange lines—vacuum part, black lines—communication part, green lines—working ground of the station).

The main component of the lab bench—a discharge chamber with a contact system.

Two high-voltage test sets were used to power the described laboratory bench, as required: 50 or 110 kV. They consisted of an oil-immersed transformer, a capacitive measuring divider and a control panel to operate the set.

The unloading chamber of the laboratory workstation was connected via a pumping channel to a set of vacuum pumps: a preliminary rotary pump and a turbomolecular pump. Precise metering valves were used to dose selected technical gases and their mixtures into the unloading chamber. The measurement processes were controlled and pressure readings were taken from a computer unit that was connected to a set of vacuum pumps and a control panel. A block diagram showing all the elements of the laboratory station in question is shown in Figure 5.

![Figure 4](image1)

**Figure 4.** The main component of the lab bench—a discharge chamber with a contact system.

![Figure 5](image2)

**Figure 5.** Block diagram of a laboratory station designed to test electrical strength of a vacuum insulation system (blue lines—low-voltage part, red lines—high-voltage part, orange lines—vacuum part, black lines—communication part, green lines—working ground of the station).
In the laboratory bench described above, pressure measurements were taken during the high-voltage tests using a vacuum gauge mounted on the vacuum pump set. Before the target electrical strength tests, the pressure difference between this point and the discharge chamber had to be determined. Direct measurement in the discharge chamber posed a risk of damaging the measurement head, especially during the discharges occurring inside. Therefore, scaling of the system was performed under de-energized conditions using two vacuum meters: one mounted at the vacuum pumps and the other mounted directly on the discharge chamber. Additionally, when reading the pressure values from the vacuum gauges, it was necessary to take into account the calibration factors and characteristics provided by the head manufacturer, for each of the gases used in the measurements. Once these factors were taken into account, the actual pressure value in the discharge chamber was correctly determined during electrical strength testing [8,29].

An appropriate test methodology was adopted to guarantee that the tests of the electrical strength of the vacuum insulation system were properly conducted. The first step consisted of connecting the low-voltage circuits, high-voltage circuits, control circuits, communication circuits, as well as grounding the relevant parts of the test system. Then, a test object was mounted inside the discharge chamber–contact pads made of tungsten filtered with copper W-Cu (70% W and 30% Cu) (Figure 6).

The next step was to introduce a selected technical gas into the discharge chamber. After pumping out the air from inside the system, the vacuum set was completely turned off so that the technical gas connected to the pumping channel was sucked in through the electronic air valve. This process was repeated three times so that after the gases were pumped out of the chamber and a vacuum was obtained with residual gases in the form of a selected noble gas, it was possible to set the final pressure value.

There are two ways to conduct electrical strength tests with varying residual gas pressure inside the chamber and a fixed contact gap. The first way is to start with a higher pressure (lower vacuum) and decrease the pressure (increase the vacuum) in successive measurements. The second way consists of carrying out measurements starting from a high vacuum, and gradually increasing the pressure using the chosen gas. The results presented in this paper were obtained using the second method.

The final step was to set the selected contact gap and determine the test sample parameters and start the measurement. The system automatically increased its value at a specified voltage increase rate of 1 kV/s until an electrical breakdown occurred between the contacts.
3. Results

The electrical strength of the vacuum insulating system was investigated for air and three noble gases: argon, neon, and helium, for two contact gaps \( d \) equal to 1 mm and 2 mm. The pressure range of residual gases in the discharge chamber was chosen from a value equal to \( 3.0 \times 10^{-3} \) Pa to the pressure value at which the electrical strength of the system decreased to a level equal to about 2.0 kV. The pressure range in which the measurements were carried out, is presented in Table 2, while Figure 7 shows the obtained results of the breakdown voltage measurements as a function of the residual gas pressure in the discharge chamber.

**Table 2.** The pressure range at which electrical strength measurements were made.

| Residual Gas Type | Pressure Range \( d = 1 \) mm | Pressure Range \( d = 2 \) mm |
|-------------------|-------------------------------|-------------------------------|
| Air               | \( 3.0 \times 10^{-3} \div 6.0 \times 10^{-1} \) Pa | \( 3.0 \times 10^{-3} \div 6.0 \times 10^{-1} \) Pa |
| Hel               | \( 3.0 \times 10^{-3} \div 8.0 \times 10^{-1} \) Pa | \( 3.0 \times 10^{-3} \div 1.0 \times 10^{0} \) Pa |
| Argon             | \( 3.0 \times 10^{-3} \div 1.0 \times 10^{0} \) Pa | \( 3.0 \times 10^{-3} \div 2.0 \times 10^{0} \) Pa |
| Neon              | \( 3.0 \times 10^{-3} \div 4.0 \times 10^{0} \) Pa | \( 3.0 \times 10^{-3} \div 4.0 \times 10^{0} \) Pa |

First of all, note the two ranges for each characteristic. There is a certain pressure value below which the electrical strength of the system maintains a constant value, while above this value, the electrical strength decreases rapidly. These values are summarized in Table 3.

**Figure 7.** Dependence of the breakdown voltage \( U_d \) as a function of the residual gas pressure \( p \) (argon, air, neon, and helium) for contact gaps: (a) \( d = 1 \) mm, (b) \( d = 2 \) mm.
Table 3. The pressure range at which electrical strength measurements were made.

| Residual Gas Type | $d = 1$ mm | $d = 2$ mm |
|-------------------|------------|------------|
|                   | $p$        | $p$        |
| Argon             | $3.0 \times 10^{-1}$ Pa | $2.0 \times 10^{-1}$ Pa |
| Air               | $4.0 \times 10^{-1}$ Pa | $3.5 \times 10^{-1}$ Pa |
| Neon              | $5.0 \times 10^{-1}$ Pa | $4.0 \times 10^{-1}$ Pa |
| Helium            | $2.0 \times 10^{0}$ Pa  | $2.0 \times 10^{0}$ Pa  |

Below the pressure values summarized in Table 3, the electrical strength at a contact gap of $d = 1$ mm, reached a value equal to about 13–14 kV for each type of residual gas and about 18–20 kV at a contact gap of $d = 2$ mm.

A constant value of electrical strength over the largest pressure range occurred for helium, as the inflection point of the strength characteristics occurred at a pressure equal to $2.0 \times 10^{0}$ Pa for each of the contact gaps tested (1 mm and 2 mm). For neon, this point occurred at pressures of $4.0 \times 10^{-1}$ Pa and $4.0 \times 10^{-1}$ Pa, respectively, while for air the values were $4.0 \times 10^{-1}$ Pa and $3.5 \times 10^{-1}$ Pa. The smallest pressure interval at constant strength has argon. The inflection point occurred at a pressure equal to $3.0 \times 10^{-1}$ Pa for $d = 1$ mm and $2.0 \times 10^{-1}$ Pa for $d = 2$ mm, respectively.

The rapid decrease in electrical strength was associated with the gradual appearance of glow discharges for each gas. Figure 8 shows the emitted light in the discharge chamber for pressures above 1 Pa.

![Figure 8](image_url)

Figure 8. Light emitted in the discharge chamber when glow discharges occur for residual gases: (a) argon, (b) helium, (c) neon, (d) air.
By passing an electric current through a given gas, its atoms are excited. As the electrons return to the lower shell, they radiate the excess energy in the form of visible light observed in the discharge chamber. The different subshell of each element causes light waves of different wavelengths to be emitted, hence the different colors of the glow discharge. Discharges of this type have been the subject of many publications in recent years. The analysis of glow plasma in noble gas environments, and in both DC and AC powered systems has appeared in [30–34], among others. The position described in this paper provides advanced methods for the analysis of this type of physical phenomena, so that the subsequent research work of the authors will also include phenomena of this type.

Further measurements of the electrical strength with increasing pressure values in the discharge chamber would make it possible to determine the minimum of the Paschen curve and to plot the right branch of this curve. However, this is not of interest to the authors of this paper.

After completing a series of electrical strength tests at an AC voltage with a mains frequency of \( f = 50 \text{ Hz} \), the contact pads were disassembled and photographed. Figure 9 shows their appearance. The left overlay was mounted on a grounded electrode, while the right overlay was mounted on a high voltage electrode. Analyzing the condition of these overlays, one can see a fairly regular distribution of electrical breakdown marks. These marks are distributed over the entire surface of both overlays. This indicates a uniform distribution of electrostatic forces acting on the electrodes. Compared to DC voltage, the electrical breakdowns occurring at AC voltage with mains frequency distort the electrode surfaces to a greater extent.

![Figure 9. Appearance of contact pads after a series of electrical strength tests: (a) grounded electrode, (b) high voltage electrode.](image)

In recent years, research papers have been published in relation to the analysis of the effect of electric breakdown in a vacuum on the surface condition of electrodes made of W-Cu material. This is related to the ongoing development of various types of switching equipment, and thus the requirements for contact materials to withstand higher voltage values, with the best possible technical parameters [35].

In [36], the microstructure of W-Cu contacts after the occurrence of an electrical breakdown in a vacuum was analyzed and the vacuum arc burning process was studied. The authors found that cathodic spots occurred in the Cu phase during the first breakdown. After the occurrence of the electrical breakdown, molten Cu droplets were sprayed from the cathode spots and observed by an ultrafast digital video camera. Figure 10 shows the surface morphology of the W\textsubscript{70}Cu\textsubscript{30} alloy after the electrical breakdown.
The experimental results of this work mainly showed that W-Cu alloys with higher copper content had a higher erosion rate, compared to alloys with higher tungsten content under the same erosion conditions. Moreover, under fewer electrical breakdowns, contact surfaces with higher copper content were more likely to have erosion on them. Under conditions of more electrical breakdowns, W-Cu alloys with higher tungsten content were more susceptible to ablation phenomena.

Figure 11 shows a photograph taken with an optical microscope, of the contact surfaces after the electrical strength measurements described in this paper.
Figure 12. Surface microstructure of W70Cu30 after electrical strength tests were performed.

The surface of the contacts consists of clearly visible Cu grains with sizes ranging from 20 to 50 µm placed in a matrix of W. In addition to this, regularly spaced pitting caused by the electrical surges that occurred during the tests is clearly visible. A high surface roughness is also visible; therefore, the electrode surface should be mechanically polished before the next series of tests.

4. Conclusions

The analysis of the electrical discharge initiation in vacuum insulation systems with residual gases in the form of air and noble gases such as argon, neon or helium allowed us to determine the boundary conditions concerning the discharge development mechanisms in these systems. It was found that among the studied residual gases, helium has the highest free path of electrons and molecules, while argon has the lowest, which is directly related to the diameter of the gas molecule. On the basis of the calculations performed, it was observed that the change in the discharge development mechanism (from vacuum to gas discharge) occurs at the highest residual gas pressure values in the form of helium, while at the lowest residual gas pressure values in the form of argon. At the above-calculated pressure values, the electrical breakdown is possible through the development of electron avalanches, while below these pressure values, the development of discharges occurs as a result of physical phenomena occurring in the surface contact areas of the system. In the theoretical part of the article, the hypotheses of electrical breakdown initiation under such conditions, which are related to the mechanism of charged particle exchange, field emission of electrons, microparticles and the phenomenon of desorption, are described in detail.

The paper presents the results of the electrical strength tests of a contact system made of copper-filtered tungsten (70% W, 30% Cu), placed in a vacuum discharge chamber in which pressure was increased by injecting air and three noble gases: argon, neon and helium. A significant difference was observed in the chamber pressure at which the tested systems lost its insulating properties. At a contact gap of 2 mm, for the helium-filled chamber, the decrease in the electrical strength of the system occurred at the highest pressure value, equal to 2.0 × 10⁻¹ Pa, while for the neon-filled chamber this occurred at a value equal to 4.0 × 10⁻¹ Pa. These two gases, compared to air and argon, maintained their full insulating capacity in larger pressure ranges. In the case of air, the decrease in strength occurred at a pressure value equal to 3.5 × 10⁻¹ Pa, and for argon, at 2.0 × 10⁻² Pa (for a contact gap of 2 mm).

The above differences provide an alternative for the insulating medium used in vacuum chambers used in electric power switching apparatus. The vacuum-extinguishing chambers currently used in power switching apparatus are characterized by a rated operating pressure of 10⁻³ Pa. Thanks to the use of, for example, neon or helium, it is possible to increase the nominal working pressure of such a chamber, for example, to 10⁻² Pa for
neon or 10⁻¹ Pa for helium, maintaining its full insulating capacity. Increasing the working pressure rating of a vacuum chamber will make it easier to maintain its tightness, and thus reduce the likelihood of it leaking. In addition, the use of gases such as helium or neon are environmentally-friendly and contribute to a reduction in greenhouse gas emissions into the atmosphere.

In the further scientific work of the authors of this article, it will be necessary to verify the proposed insulating media in terms of the physical phenomena that occur during switching operations, i.e., mainly the processes of electric arc burning and the occurrence of overvoltages when it is its extinguished.

**Author Contributions:** P.W. proposed the study of electrical strength of vacuum insulating systems in the environment of selected noble gases at AC voltage and guided the work. M.L. did the calculations and wrote the paper. P.W. and M.L. revised the results and contributed to the discussions. All authors have read and agreed to the published version of the manuscript.

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**References**

1. Lisovskiy, V.A.; Yakovin, S.D.; Yegorenkov, V.D. Low-pressure gas breakdown in uniform dc electric field. *J. Phys. D Appl. Phys.* 2000, 33, 2722–2730. [CrossRef]
2. Marić, D.; Malović, G.; Petrović, Z.L. Space–time development of low-pressure gas breakdown. *Plasma Sources Sci. Technol.* 2009, 18, 034009. [CrossRef]
3. Fu, Y.; Yang, S.; Zou, X.; Luo, H.; Wang, X. Effect of distribution of electric field on low-pressure gas breakdown. *Phys. Plasmas* 2017, 24, 023508. [CrossRef]
4. Pejovic, M.M.; Ristic, G.S.; Karamarkovic, J.P. Electrical breakdown in low pressure gases. *J. Phys. D Appl. Phys.* 2002, 35, 91–103. [CrossRef]
5. Lisovskiy, V.A.; Osmayev, R.; Gapon, A.; Dudin, S.; Lesnik, I.; Yegorenkov, V. Electric field non-uniformity effect on dc low pressure gas breakdown between flat electrodes. *Vacuum* 2017, 145, 19–29. [CrossRef]
6. Wijsman, R.A. Breakdown probability of a low pressure gas discharge. *Phys. Rev.* 1949, 75, 833–838. [CrossRef]
7. Lisovsky, V.A.; Yegorenkov, V.D. Low-pressure gas breakdown in combined fields. *J. Phys. D Appl. Phys.* 1994, 27, 2340–2348. [CrossRef]
8. Węgierek, P.; Lech, M.; Kostyla, D.; Kozak, C. Study on the Effect of Helium on the Dielectric Strength of Medium-Voltage Vacuum Interrupters. *Energies* 2021, 14, 3742. [CrossRef]
9. Gortschakow, S.; Franke, S.; Methling, R.; Gonzalez, D.; Lawall, A.; Taylor, E.D.; Graskowski, F. Properties of Vacuum Arcs Generated by Switching RMF Contacts at Different Ignition Positions. *Energies* 2020, 13, 5596. [CrossRef]
10. Hashemi, E.; Niayesh, K. DC Current Interruption Based on Vacuum Arc Impacted by Ultra-Fast Transverse Magnetic Field. *Energies* 2020, 13, 4644. [CrossRef]
11. Woodruff, K.; Baeza-Rubio, J.; Huerta, D.; Jones, B.J.P.; McDonald, A.D.; Norman, L.; Norman, D.R.; Adams, C.; Álvarez, V.; Arai, L.; et al. Radio Frequency and DC High Voltage Breakdown of High Pressure Helium, Argon, and Xenon. *J. Instrum.* 2020, 15, P04022. [CrossRef]
12. Park, H.; Lim, D.-Y.; Bae, S. Surface Discharge Mechanism on Epoxy Resin in Electronegative Gases and Its Application. *Appl. Sci.* 2020, 10, 6673. [CrossRef]
13. Węgierek, P.; Lech, M.; Kozak, C.; Pastuszak, J. Methodology for testing the electric strength of vacuum chambers designed for modern medium voltage switchgear. *Metrol. Meas. Syst.* 2020, 27, 687–700. [CrossRef]
14. Lee, W.-Y.; Jun, J.-U.; Oh, H.-S.; Park, J.-K.; Oh, Y.-H.; Song, K.-D.; Jang, H.-J. Comparison of the Interrupting Capability of Gas Circuit Breaker According to SF₆, SF₅Cl, and CO₂/O₂ Mixture. *Energies* 2020, 13, 6388. [CrossRef]
15. Opydo, W. Właściwości Gazowych i Próżnionych Wysokonapięciowych Układów Izolacyjnych; Wydawnictwo Politechniki Poznańskiej: Poznań, Poland, 2008; pp. 24–26, ISBN 978-83-7143-348-1.
16. Hałas, A. Technologia Wysokiej Próżni; Państwowe Wydawnictwo Naukowe: Warszawa, Poland, 1980; pp. 27–37, ISBN 83-01-00845-8.
17. Opydo, W.; Ranachowski, J. Właściwości Elektryczne Próżniowych Układów Izolacyjnych Przy Napięciu Przemiennym; Wydawnictwo Naukowe PWN: Poznań, Poland, 1993; pp. 106–113, ISBN 830112212.

18. Li, S.; Geng, Y.; Liu, Z.; Wang, J. “V” shape curves of physical parameters of field emitters versus applied voltage toward breakdown in vacuum. *IEEE Trans. Dielectr. Electr. Insul.* 2018, 25, 749–755. [CrossRef]

19. Li, S.; Geng, Y.; Liu, Z.; Wang, J. Dependence of field enhancement factor on power frequency voltage in vacuum. In Proceedings of the 4th International Conference on Electric Power Equipment—Switching Technology, Xi’an, China, 22–25 October 2017; pp. 594–597. [CrossRef]

20. Stoczko, S.; Szewczyk, M.; Pochanke, Z.; Chmielak, W. Experimental study on field emission current in vacuum interrupter at functional limit of vacuum pressure. *Electr. Pwr Syst. Ref.* 2021, 191, 106860. [CrossRef]

21. Diamond, W.T. A model of gas desorption and radiation during initial high voltage conditioning in vacuum. *J. Appl. Phys.* 2019, 126, 193303. [CrossRef]

22. Balachandra, T.C.; Shaik, H. Breakdown and Prebreakdown Conduction in Plain Vacuum Gaps under Variable Frequency Alternating Excitations. In Proceedings of the 2019 Innovations in Power and Advanced Computing Technologies (i-PACT), Vellore, India, 22–23 March 2019; pp. 1–4. [CrossRef]

23. Greenwood, A. Vacuum Switchgear; The Institution of Engineering and Technology: London, UK, 2007; pp. 49–58, ISBN 978-0-85296-855-0.

24. Todorović, R.; Škatarić, D.; Bajramović, Z.; Stanković, K. Correlation and regression between the breakdown voltage and pre-breakdown parameters of vacuum switching elements. *Vacuum* 2016, 123, 111–120. [CrossRef]

25. Klas, M.; Čermák, P.; Borkhari, A.F.; Satrapinskyy, L.; Matejčík, Š.; Radjenović, B.; Radmilović-Radjenović, M. Vacuum breakdown in microgaps between stainless-steel electrodes powered by direct-current and pulsed electric field. *Vacuum* 2021, 191, 110327. [CrossRef]

26. Li, S.; Geng, Y.; Liu, Z.; Wang, J.; Yamano, Y.; Okura, T.; Kyosu, R.; Nishiyama, M. Discharge and Breakdown Mechanism Transition in the Conditioning Process Between Plane-Plane Copper Electrodes in Vacuum. *IEEE Trans. Dielectr. Electr. Insul.* 2019, 26, 539–546. [CrossRef]

27. Li, S.; Yamano, Y.; Geng, Y.; Liu, Z.; Wang, J. Gas desorption induced discharge in vacuum and its polarity effect. *IEEE Trans. Dielectr. Electr. Insul.* 2020, 27, 799–805. [CrossRef]

28. Ejiri, H.; Abe, K.; Kikuchi, Y.; Kumada, A.; Hidaka, K.; Donen, T.; Tsukima, M. Motion and Production of Microparticles in Vacuum Interrupter. *IEEE Trans. Dielectr. Electr. Insul.* 2017, 24, 3374–3380. [CrossRef]

29. Lech, M.; Kostyla, D. Method For Determining The Actual Pressure Value in a MV Vacuum Interrupter. *Inform. Autom. Pomiaty Ochr. Sro. IAPGOS* 2021, 1, 28–31. [CrossRef]

30. Gagnon, H.; Piyakis, K.; Wertheimer, M.R. Energy Dissipation in Noble Gas Atmospheric Pressure Glow Discharges (APGD). *Plasma Process. Polym.* 2014, 11, 106–109. [CrossRef]

31. Kongpiboolkid, W.; Mongkolnavin, R. Plasma characteristics of argon glow discharge produced by AC power supply operating at low frequencies. *AIP Conf. Proc.* 2015, 1657, 150004. [CrossRef]

32. Tangiitsomboon, P.; Ngamrungroj, D.; Mongkolnavin, R. Comparison of electron temperature in DC glow discharge and AC glow discharge plasma. *J. Phys. Conf. Ser.* 2019, 1380, 012022. [CrossRef]

33. Li, X.; Yang, D.; Yuan, H.; Liang, J.; Xu, T.; Zhao, Z.; Zhou, X.; Zhang, L.; Wang, W.; Li, X. Detection of trace heavy metals using atmospheric pressure glow discharge by optical emission spectra. *High Volt.* 2019, 4, 228–233. [CrossRef]

34. Yao, J.; Yuan, C.; Yu, Z.; Zhou, Z.; Kudryavtsev, A. Measurements of plasma parameters in a hollow electrode AC glow discharge in helium. *Plasma Sci. Technol.* 2019, 22, 034006. [CrossRef]

35. Hou, C.; Song, X.; Tang, F.; Li, Y.; Cao, L.; Wang, J.; Nie, Z. W–Cu composites with submicron- and nanostructures: Progress and challenges. *NPG Asia Mater.* 2019, 11, 74. [CrossRef]

36. Wei, X.; Yu, D.; Sun, Z.; Yang, Z.; Song, X.; Ding, B. Arc characteristics and microstructure evolution of W-Cu contacts during the vacuum breakdown. *Vacuum* 2014, 107, 83–89. [CrossRef]

37. Chen, W.; Dong, L.; Zhang, Z.; Gao, H. Investigation and analysis of arc ablation on WCu electrical contact materials. *J. Mater. Sci. Mater. Electron.* 2016, 27, 5584–5591. [CrossRef]