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Breakdown processes
in HID lamps

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Summary

This thesis presents the results of experimental and modelling studies of breakdown processes in near-atmospheric pressure noble gasses. The motivation came from the lighting industry - our goal was to provide a better understanding of the breakdown phenomena in conditions typical for a mid-pressure high-intensity discharge (HID) lamp. However, many parts of the research can be used in a broader spectrum of applications involving breakdown, for example in high power electronics, in removal of unwanted electric charges, photocopying, handling waste, UV generation or surface treatment. We focused our research to mid-pressure (0.1 to 1 bar) discharges in argon and xenon with varying conditions that will prove to greatly influence the breakdown process.

First, we examined the effect the dielectric surfaces have on the breakdown process. A pin-to-pin electrode geometry was placed in close vicinity of a flat dielectric in an argon atmosphere of pressure varying between 0.1 and 1 bar. We used positive pulsed voltages on the charged electrode (rise time varying between 47 and 100 V/ns), observed the development and measured the speed of the discharge forming on the dielectric surface and in the gas between the electrode tips. Our results show that surface discharges use propagation and growth mechanisms that are in some aspects different from the discharges that form in the gas.

The effect of the voltage form on the breakdown process was subsequently studied. Lowering of the breakdown voltage of lamps is a constant goal to be met, and it has already been observed that substituting pulsed voltages for AC in the 100-kHz range brings significant improvements. We performed electrical and optical measurements of the breakdown parameters and explained why AC breakdown works on lower voltages than pulsed breakdown. The differences between the discharges in different gasses were explained, along with the influ-
ence of voltage frequency on the breakdown process and UV- and \(^{85}\text{Kr}\)-related effects. Statistical lag times were calculated for different parameters.

A valuable contribution to the understanding of the AC ignition process was done by using computer simulations. A fluid model and a cylindrically symmetric 2D geometry with a pin-to-pin electrode configuration was used to simulate a 700 mbar argon discharge. After simulating pulsed ignition in free gas and proving the importance of metastables on the discharge growth, the AC breakdown process in a lamp-like geometry was also simulated at frequencies between 60 kHz and 1 MHz. The main finding of this part of the research was the explanation why AC breakdown requires lower voltage than pulsed breakdown. We also explained the influence of the voltage frequency observed in experiments.

The final part of the research considered the influence of external structures ("antennas") on the breakdown process in AC discharges. Antennas are thin metallic formations on the outer surface of the lamp burner. An EM model was used to examine the influence of different antenna structures on the electric field enhancement in the lamp in a static case. We have also done a series of experiments on lamps, showing that the antennas significantly lower the breakdown voltage. The last part of the thesis shows how antennas work, why the active ones work better than the passive ones, and the reason behind the observed differences in the workings of the passive antennas.
Samenvatting

Dit proefschrift behandelt experimenteel en modelmatig onderzoek aan doorslagprocessen in edelgassen onder atmosferische druk. De motivatie hiervoor kwam vanuit de verlichtingsindustrie - ons doel was om een beter begrip te krijgen van de doorslagprocessen in omstandigheden die representatief zijn voor midden-druk High Intensity Discharge (HID) lampen. Echter, de resultaten van het onderzoek kunnen ook worden gebruikt in een breder spectrum van toepassingen, bijvoorbeeld in de hoogvermogenselektronica, in de verwijdering van ongewenste elektrische ladingen, fotokopiëren, behandeling van afval, UV-opwekking of oppervlaktebehandeling. We hebben ons onderzoek in 0.1 tot 1 bar ontlasting in argon en xenon gedaan, onder wisselende omstandigheden die grote invloed op het doorslagproces zullen blijken te hebben.

Eerst onderzochten we het effect van de diëlektrische oppervlakken op het doorslagproces. Een *pin-to-pin* elektrode geometrie werd geplaatst vlakbij een vlak diëlektricum. Het experiment werd in een argon atmosfeer gedaan, bij een druk die varieerde tussen 0.1 en 1 bar. We hebben positieve gepulste spanningen op de bekrachtigde elektrode gebruikt. De snelheid van de ontlasting die zich vormden op het diëlektrisch oppervlak en in het gas tussen de elektrodes werd ook gemeten. Onze resultaten laten zien dat de ontlasting op oppervlakken enkele groeimechanismen gebruiken die in sommige opzichten verschillen van de ontlasting die zich in het gas vormen.

Vervolgens werd het effect van de spanningsvorm op het doorslagproces onderzocht. Verlaging van de ontsteekspanning van lampen is een voortdurende doelstelling, en het is reeds vastgesteld dat vervanging van gepulste spanningen door AC spanningen substantiële verbeteringen met zich meebrengt. We voerden elektrische en optische metingen uit en hebben kunnen uitleggen waarom AC ontsteking bij lagere spanningen mogelijk is dan gepulste ontsteking. De
verschillen tussen de ontladingen in de verschillende gassen werden uitgelegd, samen met de invloed van de spanningsfrequentie op het doorslagproces en UV- en $^{85}$Kr-gerelateerde effecten. Stochastische vertragingseffecten werden berekend voor verschillende parameters.

We hebben een waardevolle bijdrage geleverd aan het begrip van het AC ontsmetingproces door middel van computersimulaties. Een vloeistofmodel en een 2D-geometrie met cilindrische symmetrie met een pin-to-pin configuratie van elektroden werden gebruikt om een 700 mbar argon ontlading te simuleren. De simulaties van deze gepulste elektrische ontsmeting hebben het belang van metastabiele atomen aangetoond. De AC doorslag in een lamp-achtige geometrie is ook gesimuleerd bij frequenties tussen 60 kHz en 1 MHz. De belangrijkste bevinding van dit deel van het onderzoek was de verklaring waarom AC ontsmeting een lagere spanning vereist dan gepulste ontsmeting. We hebben ook een beter begrip van de invloed van de spanningsfrequentie in experimenten gekregen.

Het laatste deel van het onderzoek gaat over de invloed van externe structuren (“antennes”) op het doorslagproces in AC ontladingen. Antennes zijn dunne metalen structuren aan de buitenkant van de ontladingsschijf. Een EM-model werd gebruikt om de invloed van verschillende antennestructuren te onderzoeken. We hebben ook experimenten aan lampen gedaan, waaruit blijkt dat de antennes de doorslagspanning aanzienlijk verlagen. Het laatste deel van het proefschrift laat zien hoe antennes werken, waarom de actieve antennes beter dan de passieve zijn, en verklaart de waargenomen verschillen in werking van diverse passieve antennes.
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1

Introduction

1.1 Lighting

Lamps are so common that they are taken for granted. However, life without artificial lighting would look much different than what we are used to. Daily activities today do not depend on the weather conditions or the season we find ourselves in; this allows for the evolution of technology, science and art. There are millions of people staying at work after the sun has gone down in the winter months, performing their jobs and making our world possible. However, they rarely look up to examine the light emitters suspended above their heads.

About 20% of the world’s electricity consumption is used for lighting [1]. This criterium alone shows the major importance of good lamp design. Additionally, there are several other key features a good lamp should have, like good color rendering, which makes the colours of illuminated objects appear like they would under sunlight. The stability and the longevity of the light source are also sought-after properties. Having all this in mind, it becomes obvious that good lamp design is anything but simple - it often involves years of development and testing done by teams of experts in various fields.

Most of the light sources used today work on the principle of plasma technology. Even though the LED technology is developing fast, discharge lamps are still most qualified for general lighting applications in large areas, for indoor and outdoor lighting [2]. Gas discharge lamps convert the electric power into light by means of an electrical discharge in the gas medium. A plasma is created in the gas volume between two electrodes [3] - this is a state of gas where
an appreciable amount of the atoms and molecules are excited and ionized.

High intensity discharge (HID) lamps represent a lamp family that belongs to the larger group of discharge lamps [4]. These lamps operate at high pressure (over 1 bar) contained in a small volume and they usually contain mercury or sodium. High pressure surroundings ensure numerous collisions between electrons and heavy particles. A cumulative effect is the energy transfer from electrons to heavy particles, which results in high heavy particle temperatures, typically between 1400 and 8000 K. Consequently, the spectral power is distributed over a large range of lines, while the resonance lines are typically self-absorbed.

Even though HID lamps operate at high pressures, the conditions during the cold ignition are quite different. Mercury pressure is substantially reduced and other metals undergo transitions back to their solid phase. Consequently, a medium is needed in a cold lamp, which one can convert into plasma. For this purpose noble gasses are commonly used.

1.2 Ignition

1.2.1 Discharge lamps

The ignition process in discharge lamps comprises of a sequence of events during which the starting gas in a lamp undergoes conversion into a conductive state and finally forms an arc [5]. The breakdown stage is the first one to take place; it encompasses the transition of the gas to a conductive state usually via the Townsend or the streamer mechanism. Subsequently the discharge needs to be stabilised. This stage entails the limiting of the current through the discharge, which would otherwise, due to the negative voltage-current characteristic, rise until the lamp would be destroyed. The various stages of discharge ignition have been portrayed in the case of low pressures in a homogenous electric field [6,7] and are schematically shown in figure 1.1. The current-potential curve in the case of discharge lamps has been shown to have roughly the same complex shape [5].

In the beginning stage, denoted as I in the figure, when low-level voltage is applied to the electrode gap in a neutral gas atmosphere, primary electrons in the gas liberated by either photoemission from the cathode, radioactive decay or by cosmic radiation, move to the anode. This causes low-level current to
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Figure 1.1: The current-voltage characteristics of a DC discharge [5]. The current and voltage ranges for the are merely illustrative.

flow through the gap in this 'Geiger' stage of ignition. No significant ionization takes place and the discharge relies on external sources of ionization. In order to increase the current, higher voltage must be applied. Consequently, the electrons are accelerated in the electric field, undergoing a series of elastic and inelastic collisions. New electrons are generated in inelastic collisions, and the resulting macroscopic current depends on their production rate.

When a high enough electric field is achieved, the discharge becomes self-sustaining and current breakdown is reached. This is shown as a crossing point between stage I and II in figure 1.1. At this point each electron in the electrode gap produces at least one secondary electron by means of ionization. Voltage at this level is called the breakdown voltage and it is a function of several parameters - gas type and pressure, electrode gap, electrode material and radius of curvature, voltage shape and slope.

Between the current and the voltage breakdown, in stage II, the current increases several orders of magnitude as a result of just a slight increase of voltage. This is partly due to the exponential form of the Townsend first ionization coefficient as a function of the electric field; this coefficient determines the ionization rate in the electrode gap. According to the Townsend theory, secondary electron emission processes take place as well, and are the primary cause of the steep current increase. This stage of the discharge development is called the 'Townsend discharge' or the 'dark discharge', as there is very little
light emitted.

At the point of voltage breakdown, crossing from stage II to stage III, the voltage across the electrode gap drops significantly and the discharge crosses to the next stage of its development - the 'subnormal glow discharge' (stage III). The total ionization yield is an exponential function of the electric field, and the potential difference in the electrode gap is confined to the space near the cathode, which causes the electric field to grow in that region. As a consequence, the current through the discharge can increase even with a decrease of voltage across the gap. The total current is now determined by the discharge itself as well as the external electrical circuitry.

In the 'glow discharge' stage (number IV in the figure), the voltage stays constant while the current through the discharge keeps increasing, due to the extension of the discharge over the electrode surface. Subsequently, during the 'abnormal glow discharge' stage (stage V in the figure), the whole electrode surface is covered by the discharge and the increase of current can continue only by increasing the ionization rate. This can be done by increasing the potential difference, thereby effectively increasing the electric field in the electrode gap. When ample thermionic emission becomes possible as a consequence of cathode heating, another voltage drop with the increase of current is observed (stages VI and VII) and the transition to the 'arc discharge', which is the final stage of the ignition process.

1.2.2 Breakdown

This thesis deals with the first stages (I and II) of the development of the discharge in a noble gas atmosphere, not only specific for HID lamps, but common in several other application areas. This is a transient phenomenon in which a body of neutral gas becomes conducting and it is referred to as breakdown. Simply put, breakdown entails the multiplication of electron avalanches. The multiplication factor $M = \gamma \exp(\alpha d)$ is often used to characterize breakdown-associated phenomena. It gives the number of electron-ion pairs produced in the gap by the passage of one electron avalanche, according to the Townsend theory.

The product of gas pressure $p$ and the length of the electrode gap $d$ has been empirically identified as a parameter essential for expressing the breakdown characteristics (breakdown voltage) of an homogenous electrode gap by
F Paschen in the late 19th century [8]. The *Paschen curves* show the breakdown voltage for a particular gas as a function of the \( pd \) product. At this voltage, the multiplication factor \( M \) is approximately equal to one. The observations made by Paschen were explained by Townsend and the proposed breakdown mechanism was named the *Townsend mechanism*. It should be noted, though, that the Paschen curve as well as the derivations in the subsequent section on Townsend mechanism are only valid for a parallel-plate (essentially 1-D) situation which is far from practical reality in discharge lamps and many other applications.

The increase in voltage causes the multiplication factor \( M \) to steeply rise, as the factor \( \alpha \) - Townsend first ionization coefficient - is an exponential function of the electric field. \( M \) determines the formation time of the discharge. In the case when \( \alpha d \) exceeds 20 [9], a localized space-charge region is created by the succession of electron avalanches in the electrode gap. This space charge focuses the electric field and drives the development of a conducting streamer channel [10].

More about the Townsend and the streamer mechanism can be found in the following two sections.

### 1.2.3 Townsend mechanism

Townsend was among the first scientists to study the variation of the current through gas discharges placed in a two-plane electrode system. He used UV irradiation to produce ample photoelectrons from the cathode surface to ensure a steady supply of initial free electrons at the beginning of the breakdown process [9]. He was the first to measure the current-voltage characteristic during the various stages of the breakdown process.

As the discharge crosses from the 'Geiger' stage as described above to the stage of the 'Townsend discharge', the steep increase in current is ascribed to the ionization of the gas by electron collisions. The increase in the number of electrons \( dn \) at the distance \( x \) from the cathode is given by [11]

\[
\frac{dn}{dx} = (\alpha - \eta)n
\]  

(1.1)

The parameters \( \alpha \) and \( \eta \) are the ionization and loss coefficients and they typically depend on the gas type, pressure and the electric field. \( \alpha - \eta \) is the effective ionization coefficient. At the distance \( x = d \), the number of electrons
is given by an exponential function

\[ n = n_0 \exp((\alpha - \eta)d) \]  

(1.2)

Because of the exponential nature of electron multiplication process in the case when the effective ionization has a positive value, this process was named the *electron avalanche*. The corresponding current is given by

\[ i = i_0 \exp((\alpha - \eta)d) \]  

(1.3)

In this case \( i_0 \) is the primary photocurrent, while the \( n_0 \) is the number of primary electrons generated at the cathode.

During the 'Townsend discharge' stage, the current was observed to rise faster than exponentially. This was explained by Townsend as a consequence of other processes, like inelastic collisions to form metastable or radiatively excited states of neutral atoms or molecules. Consequently, positive ions, photons and metastables were thought to be available in the gas to enable production of secondary electrons emitted either in gas or at the cathode. While scientists largely agreed with the theory of secondary electron emission from the cathode surface, most of them voiced their scepticism towards the same effect in the gas volume, arguing that the positive ions are not likely to gain enough energy to enable this process.

Including the secondary electron emission into the theory and neglecting \( \eta \), the number of electrons reaching distance \( d \) per second is given by

\[ n = n_0 \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \]  

(1.4)

The parameter \( \gamma \) is the number of electrons released from the cathode per incident positive ion and it is called the second Townsend ionization coefficient. The current is therefore given as

\[ i = i_0 \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \]  

(1.5)

\( \gamma \) can represent one or more secondary electron emission mechanisms, as it has been shown that the resulting electron density has the same form when considering other secondary electron emission mechanisms.

At low overvoltages, the value of \( \gamma(e^{\alpha d} - 1) \) is close to zero and the aforementioned expression takes the form of the equation derived for the case without
the secondary electron emission mechanisms. A singularity is reached when 
\( \gamma(e^{\alpha d} - 1) = 1 \). At this point, the current becomes indeterminate, and accordin-
g to the original theory suggested by Townsend, this point signifies the onset 
of a spark. In general, \( e^{\alpha d} \gg 1 \), and the condition can be written as

\[ \gamma e^{\alpha d} = 1 \]  \hfill (1.6)

The significance of Townsend sparking criterion has been widely discussed
and the following conclusions have been drawn [9]. In the case when \( \gamma e^{\alpha d} < 1 \),
the current \( i \) is not self-maintained and ceases upon the removal of the pho-
tocurrent \( i_0 \). When the criterion is met, the multiplication factor \( M \) as defined
in the previous section is sufficiently large so that the total balance of ioniz-
ing processes in one electron avalanche and subsequent cathode bombardment
produce one secondary electron that will repeat the process. The discharge is
then self-maintaining and can continue in the absence of the outside source of
electrons. When \( \gamma e^{\alpha d} > 1 \), the ionization produced in successive avalanches is
cumulative and the spark grows rapidly.

Ionization of the gas by electron collision and the secondary electron emis-
sion from the cathode surface are chance phenomena, and the first and the
second Townsend ionization coefficients fluctuate around the mean value. The
product \( \gamma e^{\alpha d} \) varies for individual avalanches. Consequently, there is an aver-
age breakdown voltage corresponding to the criterion \( \gamma e^{\alpha d} = 1 \) and breakdown
might be possible in some cases at lower voltages as well. However, due to
the steep rate of change of the product \( \gamma e^{\alpha d} \) with the voltage gradient, the
breakdown voltage is generally very well defined.

From the breakdown voltage measurements, it is possible to relate the values
of \( \alpha/p \) and the \( E/p \) [9]. As \( \alpha/p \) and \( \gamma \) were shown to be functions of \( E/p \), it
was not difficult to theoretically prove Paschen’s law previously empirically
established. Given that the research was done in homogenous electric field,
\( E = V/d \), and the Townsend criterion can be rewritten in the following form

\[ \gamma(V/pd)e^{pd\alpha(V/pd)} = 1 \]  \hfill (1.7)

It is clear that for a given product \( pd \) there is a particular value of \( V \), and
hence \( V = V(pd) \) [9].
1.2.4 Streamer mechanism

At atmospheric pressures and distances larger than a few centimeters, the Townsend mechanism ceases to be valid. The theory about breakdown processes at high $pd$ values was developed by Loeb, Meek [12] and Raether [13]. They introduced the concept of space charge. The idea was that the streamers propagated (grew) in gas by ionizing the medium in front of them due to the high electric field present at their tips. The electric field, resulting from the charge separation at the streamer’s tip, was thought to be local and high enough to modify the background field imposed by the electrode system.

Where the Townsend theory fails

At $pd$ values larger than 1000 Torr cm (around 1 Bar cm), the Townsend theory cannot explain the observed breakdown processes. In particular, there are three major inconsistencies between the observations and the theory devised by Townsend [9].

One, the formative time of the discharge (from onset to breakdown) is measured in tens or hundreds of nanoseconds. The time it takes the ions to move to the cathode and create secondary electrons is much longer than the formative breakdown time.

Two, the influence of the Townsend secondary electron emission coefficient is not pronounced. This conclusion comes from the observation that the breakdown voltage is independent of the type of cathode material.

Three, the discharges are not uniform and diffuse. They are thin and filamentary.

The transition from the avalanche mode to the streamer mode of discharge development is closely connected to the charge present at the tip of the avalanche [14]. When the Townsend sparking condition is satisfied and the ionization is cumulatively produced in the successive avalanches, the space charge develops at the discharge tip. The space charge can grow sufficiently large to cause local amplification of electric field that in its magnitude surpasses the field imposed by the electrode system. The presence of this field can cause high ionization rates locally around the discharge tip and allow for new avalanches to start developing. The criterion for streamer onset is that the electric field produced by charge separation at the avalanche head must be approximately
equal to the electric field applied externally $[9,14]$. From this condition the critical density of charge at the streamer tip can be deduced $[9,13]$.

The total number of electrons at a distance $x$ from the starting point of the discharge in non-uniform fields is calculated in a way that is a bit more general than the one presented for the uniform fields. It allows for the effective ionization coefficient to be a function of the position in the electrode gap.

$$n = n_0 \exp \left[ \int_{0}^{x} (\alpha - \eta) dx \right] \tag{1.8}$$

$\alpha$ and $\eta$ are given as a function of energy and gas type $[15]$. It has been found experimentally that the streamers can propagate in background fields lower than needed for inception, but that there still is a minimum background field needed for streamer growth (also called the stability field). It is of the order of MV/m for negative and a few hundred kV/m for positive streamers in atmospheric air.

Finally, the streamer onset and propagation criterion is just an extension of Townsend self-sustained avalanche criterion. First, the streamer onset condition must be satisfied, i.e. the avalanches have to produce space charge dense enough to cause local electric field greater than the background electric field. For this, the field in the vicinity of the starting electrode must first be fairly high $[14]$. Second, the background electric field must be larger than the minimum needed for sustaining streamer growth.

The streamer propagation mechanism

There are two basic types of streamers - positive (cathode-directed) and negative (anode-directed) $[7]$. The basic mechanism of streamer propagation for both streamer types is ionization of the gas in front of the streamer tip due to the high electric field at the tip $[7,13,14,16,18]$. This requires some minimum amount of free electrons to be present in the gas irrespective of the discharge formation. It is, however, common to find free electrons in the surrounding gas, originating from cosmic rays or radioactive materials commonly found in man-made structures.

The growth of a negative streamer does not require a pool of free electrons at its tip, as a negative streamer can supply its own free electrons from the region that has already been ionized. In the case of a positive streamer, the free
electrons drift towards the streamer body; consequently, the streamer cannot provide its own free electrons in front of its tip. There are other mechanisms needed to explain positive streamer growth.

A commonly included streamer propagation mechanism is photoionization of the gas molecules present locally around the streamer tip. This mechanism has been most often studied for discharges in air \[7,9,14,19,24\]. The high-energy photons are thought to come from excited states at the streamer head and ionize neutral molecules in front of it. One should note that photoionization is possible only in gas mixtures, where the photon emitted from one excited neutral can ionize another. One should also note that the experiments in completely pure gasses are almost impossible to perform and that, at the same time, a very little amount of oxygen in argon atmosphere, for example, can appreciably change the discharge development \[20,25\].

These two mechanisms have in common that the ionization of the neutral gas takes place \textit{in front} of the streamer head. Charge already contained in the streamer channel does not have to be transported to the front of the streamer (in the case of positive streamers) and collisionally excite the neutral atoms and molecules. The ionization is achieved by giving energy to free electrons already present in the electrode gap irrespective of the discharge existence or by photoionization. The expendability of the fast transport of charge explains the growth of streamers at velocities greater than the electron drift in the given conditions.

As the ionization happens in front of the streamer head, one could say that there is an \textit{active volume} surrounding the tip in which the ionization processes are possible. This has been illustrated by Gallimberti in 1972 \[11\]. The volume covers the space where the electric field is high enough to sustain collisional ionization processes. Photoionization has a potential to expand the \textit{active volume}, thus effectively speeding up the discharge growth. However, it has recently been shown that photoionization plays a lesser role than was previously believed \[19,20\].

1.3 Overview of the thesis

The goal for this project was to investigate several aspects of breakdown in noble gasses and HID geometry. The choice to do experiments in pure argon and xenon was made in attempt to decouple the various effects in the ignition
sequence in HID lamps, which is in itself a very complex process. Understanding breakdown in pure gasses is the stepping stone for understanding more complex processes involving mercury and metal vapour, but also the physics behind breakdown in gas mixtures such as air.

We set out to examine a few aspects of pulsed breakdown in a pin-pin geometry, such as the influence of dielectric surfaces and the role that metastable atomic argon plays in ionization processes during pulsed breakdown in the gas volume. Both pulsed surface and gas discharges have already been researched, but there is knowledge lacking for a full description, which is especially true for surface discharges.

Experimental results of the surface discharge experiment are presented in Part I of the thesis. A pin-pin geometry was used, with a flat dielectric surface placed close to the electrode system in a way where the electric field direction was parallel to the dielectric surface we subsequently introduced. The electrodes were not in contact with the dielectric. Both discharges in gas volume and on the surface were obtained and their velocity measured and compared. The comparison of surface and gas discharges presented here is of value for both the lighting applications and for the pool of general knowledge on surface discharges, as the comprehensive theory on this topic has still not been developed. In lighting applications, this comparison aids in better understanding of non-aided and antenna-aided lamp ignition. The work done on antennas is presented in Part IV of the thesis.

Part II brings results of simulations of pulsed breakdown in argon in a pin-pin geometry. A useful property of research done using simulations is that one is often able to separate various effects present in a research topic that are practically inseparable in experiments. This is what we have done in this case. In order to probe the influence and the role of argon metastable atoms during pulsed breakdown, simulations were performed that compare breakdown properties when stepwise ionization is and is not included in the calculations.

Previously rather poorly researched topic of high-frequency AC breakdown in the frequency range where electron losses are drift dominated is presented in the three chapters of Part III. It has been previously empirically proven that substituting pulsed voltage with the AC signal significantly reduces the ignition voltage in HID lamps [26]. This part of the thesis brings results of experiments and simulations designed to discover the main characteristics of AC-driven breakdown, identify the important processes and deduce their respective roles.
Part IV of the thesis is the most application-driven part of the text. Effects of metallic structures on the outside of the lamp burner were examined for their effects on the breakdown process. This part brings results of the experiments, compares them to the results of non-aided breakdown processes in HID lamps presented in Part III and offers a theory to explain the differences between the breakdown observed using guided discharges with different antenna potentials.

The thesis is completed with concluding remarks and a general outlook.
Part I

Pulsed surface and volume discharges in argon
2

Speed of streamers in argon over a flat surface of a dielectric

Abstract. A pin-pin electrode geometry was used to study the velocities of streamers propagating over a flat dielectric surface and in gas close to the dielectric. The experiments were done in an argon atmosphere, at pressures from 0.1 to 1 bar, with repetitive voltage pulses. The dielectric surface played a noticeable role in discharge ignition and propagation. The average speed of the discharge decreased with higher pressure and lower voltage pulse rise rate. Moreover, it was higher when the conductive channel between the electrodes was formed over the dielectric rather than through the gas. Space resolved measurements revealed an increase in velocity of the discharge as it travelled towards the grounded electrode.

2.1 Introduction

High pressure discharges (0.1 to 1 bar) that travel along insulator surfaces in shapes of thin, ionized channels (also known as streamers) already have the attention of scientists. Either they want to avoid them, as is the case in high power electronics [27], or they want to use them in removal of unwanted electric charges from the surfaces of aircrafts in flight, photocopying, handling waste, UV generation [28,29], flow control [30] or water treatment [31]. The lighting industry also has an interest in understanding the role of streamer discharges in lamp ignition in the presence of dielectric wall materials.

Most of the gathered knowledge comes from electrical engineers, who have been troubled by this phenomenon for years [32–49] because material interaction with the streamer development is of significance when it comes to insulation performance. For the most part, their research was done in air and in atmospheric pressure.

2.1.1 Breakdown in gas and on insulating surface

The inception conditions for surface and gas discharges are quite similar - the necessary requirements are a free electron, an external electric field whose strength is above the critical value, and a sufficient distance between the electrodes [9]. The initial electrons may be created by natural ionization or be left over from previous discharges. Following the inception stage, once a space charge cloud has developed, the local electric field becomes strong enough to start new avalanches. The local electric field and the photoionization are the mechanisms suggested responsible for discharge growth [7]. Adding an insulator surface to the process makes it far more complex. It has been observed that the dielectric strength of the gaps change significantly [44,47,50], presumably because of the changes of ionization coefficients and transport parameters induced by the presence of the dielectric surface. Even though the cornerstone of understanding of surface discharges has been laid in the field of breakdown in gasses, we still do not have a complete apprehension of the physics of this phenomenon.

Most authors agree that the presence of the insulating surface near the growing discharge causes the distortion of the electric field [28,34,39,41,47,50,52], which influences the electric field at the streamer tip and causes the discharge to attach to the insulator surface. Also, the effective ionization and
attachment rates seem to be affected in different ways during the discharge growth, resulting in changes in growth characteristics.

2.1.2 Theory of desorption flashover

In 1977, a theory to explain the dramatic decrease of dielectric strength of gas gaps in the presence of dielectric surfaces was laid out by Avdienko and Malev [50]. At that time, the competing hypotheses were surface charge accumulation and the discharge formation in the adsorbed charge layer on the dielectric surface. They divided the flashover phenomena that had been observed until that time with respect to the dielectric conductivity. The thermal flashover was observed at surfaces with higher conductivity, where the dielectric strength of the gap decreased with the increase of temperature, irrespective of the surface shape. The thermal flashover theory makes use of the heat conduction properties of the dielectric surface.

The dielectrics with lower electrical conductivity did not show the same behaviour with the increase in temperature, but the dielectric strength of the gap did depend on the shape of the insulating surface. The theory [50] stated that the flashover on this kind of surfaces (the desorption flashover) was connected to gas desorption from the dielectric surface, or outgassing, when subject to electrical stress. By 1977, this effect has already been observed (see references in [50]), but also shown, measured or deduced from calculations later [53–55].

The work described in [54] showed that the desorbed gas is usually not the background gas in the experiment, but most probably gas adsorbed during the handling process (nitrogen, water vapour etc.). Both [54,55] agree on the importance of outgassing in surface breakdown process.

The phenomenon of desorption flashover was thought to consist of three steps [50,53,56,57]. First, high stress is applied to the insulator under which the insulating surface acquires positive charge. A hopping electron model was used to describe this phenomenon, where secondary electrons are produced by electron impact at the insulating surface. The initial electrons were assumed to be present due to natural ionization. In [57], the authors suggest that this mechanism is self-limiting and that the current of the avalanche is controlled entirely by an emission site which emits initial pre-flashover electrons. The suggested site was the triple point, the junction of the cathode, dielectric surface and the vacuum, also proposed previously [56]. Secondary electron emission by electron impact was also investigated by [43].
Next, the outgassing of the dielectric surface occurs. The electrons moving almost parallel to the dielectric surface cause gas molecules to be desorbed from the surface with great efficiency, between 100 and 200 molecules per incident electron [50]. The reason for this great efficiency is the electron trajectory directed along the insulating surface, not perpendicular to it. This value was under dispute, and various values can be found in the literature (for example, 4-8 molecules per electron in [53]). The next stage of discharge development is free electron generation in the desorbed gas layer by ordinary volume processes, subsequent charge multiplication, and breakdown (flashover).

The physical properties of the dielectric and vacuum conditions were thought not to have practically any influence on the characteristics of desorption flashover, since to form a discharge, one needs only to desorb less than one monolayer of adatoms. It is very important to notice that the theory proposed in [50] relied on the fact that the electric field in the system was parallel to the dielectric surface. In the case of guided discharges, i.e. the discharges where there is an electrode present parallel to the insulating surface [51], this condition is not met. In this case, the surface charge was expected to take a notable part in the breakdown process [50].

2.1.3 Other observations

In 1982, a simple theory was developed to explain the behaviour of the breakdown voltage of a gas gap situated at the axis of a dielectric cylinder, when the radius of the cylinder is varied [58]. The theory was postulated on the premise that breakdown will occur when the product of electron density and the average drift velocity reaches a certain value. The results of the predicted breakdown voltage were in good agreement with the experimental data.

The theories nowadays are differently focused. Several authors have shown [35,44] that the streamers usually propagate in two modes - there is a fast component over the dielectric surface and a slow one in ambient air. The most obvious explanation for this phenomenon is the modification of the electric field due to the dielectric permittivity. Other explanations were offered as well, for example that the ionization rate is altered in presence of an insulator because of electrons emitted from the dielectric surface by photoemission [35,37,41,43,46] and detachment of negative ions [38,40]. The authors suggested that these processes speed up the propagating streamers over a dielectric surface, even though they have to compete with losses due to electron and ion attachment to
the surface. It has been shown that the dynamics observed in surface discharges cannot be attributed only to the boost of bulk processes due to electric field modification near the dielectric surface [59–61].

In order to unravel the influence of an insulating surface on the basic properties of streamers, extensive measurements were done, determining streamer velocities that depend on various factors [37, 39, 46, 62]. The velocities varied greatly with the applied voltage and the electrode configurations.

Charge deposition during the formative avalanches of streamer corona was investigated, modelled [34] and measured [38, 42, 45, 63–65], along with the streamer velocities [41]. The measurements were done for various shapes of the dielectric test objects as well as for different electrode geometries, the most popular being the pin-plate geometry. The charge deposited by corona avalanches on the dielectric surface modified the growth process and lead to a reduction of the total charge generated in the corona. Allen and Faircloth [41] saw that the net charge deposited over the insulator surface was small compared to the injected corona charge. Surface charge density distribution followed the profile that the streamers form, and it increased the probability of the consecutive breakdown. The densities close to the electrodes were high, which could contribute to breakdown probabilities via high local electric fields and associated supply of initiating electrons. There was a negligible increase in deposited charge after successive coronas.

The deposited charge was also shown to hinder inception [34] or not influence it at all [40], but promote discharge growth [40]. The effect of traps in the dielectric surface was modelled [66] and found to have a large influence on the flashover properties, as it affects the charge transport. By comparing measurements done with and without UV irradiation, it was proven that in the case of nitrogen discharges, surface charge influences the discharge growth [67].

### 2.1.4 Guided discharges

According to Fouracre et al [51], guided discharges are discharges on the dielectric surface when there is an electrode (usually grounded) present on the other side of the dielectric. Many authors have done experimental [28, 51, 68, 72] or theoretical research [29, 73] into the subject.

The electric field configuration and strength in this case is much different than in the case we have been examining until now - where the electric field lines
are directed parallel to the dielectric surface. There are numerous differences between these two arrangements, but they all come down to changes in the relative influences of the effects present in both electric field configurations.

First, the dielectric permittivity plays a bigger role in the guided discharges, and its change is expected to have a greater effect on the discharge properties, especially during the growth stage. The expected effect of the permittivity was shown by [28,51]. As a result, the bulk gas ionization processes are expected to play a greater role in the guided surface discharges than in the case when the electric field is parallel to the insulating surface. Consequently, the other surface processes become less important in the overall picture. This was demonstrated in simulations done by [29]. The bulk processes played by far the most important role in the discharge growth, contributing to the overall ionization process over one order of magnitude more than the next process in line - the ionization by sheath-accelerated electrons. This effect was followed by secondary electron emission from the insulating surface and subsequently photoionization. The difference in contribution between bulk ionization and photoionization was more than three orders of magnitude.

Second, the desorption theory described previously cannot explain the phenomenon well, as the relative importance of surface charges grows with the angle between the electric field and the insulating surface [50]. The importance of surface charges in guided discharges was demonstrated by [51,68,70,74]. They concluded that the velocity of the surface discharge is strongly dependent on the charge density previously deposited on the surface. The authors of [68] even demonstrated a self-propagating surface discharge on sufficiently pre-charged surfaces. The velocities of surface discharges were found to be greatest if the surface charge of opposite polarity was pre-deposited on the surface [51,68,70].

### 2.1.5 Lighting industry

The lighting industry is currently taking an interest in surface discharges as well, as these appear to play a significant role in the ignition processes of plasma-driven lamps. This was shown in several recent investigations [26,73,76], but never systematically studied. Knowledge about surface effects in lamp burners could be used for modifying lamp ignition voltage, which is an important parameter in lamp starting: ballasts are designed to provide sufficient voltage to ignite a lamp. However, because of the stochastic nature associated with breakdown [77], a lamp will not ignite at the same voltage.
Studies done on this subject showed large variations in ignition voltage \([75,77]\). This makes lamp ignition uncertain unless its ballast provides voltage much higher than actually required for ignition. Lowering the ignition voltage or reducing its large spread would open possibilities for improvement of lamp characteristics.

The lighting industry and the electrical engineering community share an interest in surface discharges. A fundamental difference between them is that electrical engineers limit their research to atmospheric pressure air conditions, while the lighting industry is much more interested in discharges in noble gasses, in a variety of pressures. The existing knowledge is mainly on atmospheric air discharges, and there are essential differences between air and argon kinetics (e.g. detachment of electrons from negative ions). This is why we cannot directly use any theory for air in case of argon. Even so, in our experiments with argon, we have observed the same phenomena as previously reported for air (e.g. propagation in two modes - a fast component over the dielectric surface and a slow one in ambient gas) and reviewed the proposed physical processes that could be responsible for observed effects with respect to gas type. In addition, in this chapter we present a small selection of modelling results that were obtained for discharges in argon.

Appearance of the discharge in argon near a flat dielectric has already been reported on \([52]\). In this chapter we present new data on pulsed discharge velocities over a dielectric surface in argon atmosphere, obtained with a high speed iCCD camera and two different dielectric materials. We show the results of average speed measurements, as well as space resolved velocities.

2.2 Experiment

The setup is shown in figure 2.1. The negative output of a DC high voltage supply was used to charge a 1 nF capacitor through a 25 M\(\Omega\) resistor, and as the fast switch closed, a positive pulse was brought to the top electrode, while the bottom electrode was grounded. The fast semiconductor switch was necessary to ensure short rise times of our voltage pulse and low jitter. Jitter is one of the biggest challenges encountered in the study of pulsed breakdown, streamers or corona discharges \([78]\) because it keeps from obtaining sufficient time resolution in the experiment. We used a low-jitter scheme, based on the research of Briels and van Veldhuizen \([78, 80]\). The setup shown in figure
Figure 2.1: Schematic view of the electrode and dielectric geometry and the pulsed power circuit. We used an iCCD camera to photograph the discharge that formed between the electrodes. The iCCD camera was positioned perpendicular to the side of the dielectric, so that the electrode-dielectric system appeared in the photographs in the same way it is shown on the schematics.

which we used in our experiments, is a modification of their scheme. We used the Behlke HTS-361 semiconductor switch with trigger jitter of 0.1 ns, maximum withstand voltage of 30 kV and current limit of 60 A. Resistors $R_6$ limited the current through the switch and were responsible for pulse rise time. Total value of 1kΩ allowed for a fixed rise time of 150 ns.

Since the total rise time was kept constant, the rise rate had to be changed by adjustment of the peak voltage of the pulse, which means that for example for a 100 V/ns rise rate, we had to use a pulse with peak voltage of 15 kV. 100 V/ns was the fastest pulse we used. Experiments were also done with 67 V/ns and 47 V/ns pulses, which translates to 10 kV and 7 kV peak voltage, respectively.

Rod shaped tungsten electrodes were used, 0.65 mm in diameter. A flat piece of dielectric material (130 $\times$ 40 $\times$ 8 mm) was placed in the vicinity of the electrode system, as shown in figure 2.1. We used two dielectric materials - BK7 optical glass ($\epsilon_r$ between 2.3 and 4.5) and aluminum oxide ($\epsilon_r = 9.1$). The surface of aluminum oxide was slightly more rough than that of the BK7 piece, but based on the work of Tan et al [46], we expected the surface roughness not
Surface and volume discharge velocities

to have an influence on the experiment.

The distances in the system were not fixed, which allowed us to choose spacing between the tips of the two electrodes and between the electrodes and the surface of the dielectric. Since we wanted to compare the velocity of the discharge over the dielectric surface and in the gas volume between the electrodes, we chose to present three geometries that provided the conditions for acquiring both, sometimes even at the same time. The parameters are given in table 2.1.

We investigated the pressure dependence of measured velocities, that is why the electrode system was enclosed in a vacuum vessel. A Pfeiffer Vacuum rotary vane DUO 10 pump was used to control argon pressure in the vessel, in range from 100 mbar to 1 bar.

One trigger unit was used to trigger the camera and the electrical system. We examined the influence of trigger frequency on the discharge in the range from 0.2 to 25 Hz. Our investigations have shown similar behaviour for all frequencies, with breakdown voltage falling as we increased the frequency [81]. Here we present data for 1 and 25 Hz for detailed velocity measurements.

Discharge velocities were measured by means of fast photography. We used an intensified CCD (iCCD) 4Quick Edig camera from Stanford Computer Optics Inc., aligned to image the electrodes and the side of the dielectric. Photographs were taken using different delay times with respect to the trigger pulse, to image different stages of the developing discharge. The exposure time was always 5 ns. It should be mentioned that we could never take multiple pictures of the same discharge. Even so, with jitter of nanosecond order of magnitude, we were able to clearly distinguish between the photographs taken at different delay times.

2.3 Appearance of the discharge

Figure 2.2 shows photographs of discharges for three different geometries used in our experiments. All three pictures were taken at 400 mbar and pulse rise rate 100 V/ns, for the same dielectric material (BK7). One notices streamers, which is expected for a fast pulse discharge at this pressure.

The discharge propagated through the gas volume between the electrodes and reached the dielectric surface in all three cases. The mechanism responsible
Part I.

**Figure 2.2:** Photographs of discharges for three different geometries, specified in the right bottom corners. 20/12 denotes the geometry with 20 mm spacing between the electrodes and 12 mm between the electrodes and the dielectric, 20/7 marks the 20 mm - 7 mm and 30/7 specifies the 30 mm - 7 mm combination. The dielectric and the electrodes are shown in the figure, with top electrode as the anode, and the bottom one grounded. Pictures were taken with exposure times of 5 ns, at the moment very close to completion of the conductive channel between the two electrodes, for 400 mbar and 100 V/ns rise rate. The photographs are presented in false colour.

for the discharge choosing to propagate towards the dielectric is connected to the shape of the initial electric field, before the start of rapid streamer growth. It is well known that the dielectric material reacts to the applied electric field by aligning its dipoles, thereby lowering the field in its volume. As a result, the electric field outside the dielectric is increased. The difference between the electric field when the dielectric plate is close to the electrodes as opposed to the geometry in which the dielectric is further away has already been demonstrated [52]. Potential distribution was obtained from a model and it clearly showed a steep potential gradient between the electrode tip and the dielectric, which can explain the inclination of the discharge to move towards the dielectric.

One can see that the propagation path of the discharge changed as we moved the dielectric or changed the spacing between the electrodes. Even though there were streamers present in the gas volume as well as on the dielectric surface for all three geometries, the difference between these three discharges is in the location of an ionized channel that ultimately connected the two electrodes.
Surface and volume discharge velocities

Table 2.1: Geometry parameters. $s$ denotes the spacing between the tips of the electrodes, and $d$ the distance between the electrodes and the dielectric. Even though a series of combinations of $s$ and $d$ values was examined, we show discharge velocities for only three combinations of these parameters, as they represent three different modes of discharge propagation.

<table>
<thead>
<tr>
<th>cases</th>
<th>$s$ [mm]</th>
<th>$d$ [mm]</th>
<th>the discharge propagates ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>20</td>
<td>12</td>
<td>in gas</td>
</tr>
<tr>
<td>$b$</td>
<td>20</td>
<td>7</td>
<td>in gas and over the dielectric surface</td>
</tr>
<tr>
<td>$c$</td>
<td>30</td>
<td>7</td>
<td>over the dielectric surface</td>
</tr>
</tbody>
</table>

For a dielectric placed 12 mm from the electrodes (the left most picture in figure 2.2), the ionized path was formed between the electrodes, through the gas volume. On the other hand, when the dielectric was placed closer, at 7 mm distance from the electrodes, and they were placed 30 mm apart (the right most picture in figure 2.2), the ionized channel formed over the dielectric surface.

There was a mid point in the configuration, or mid region, in which the discharge propagated both over the dielectric surface and through the gas volume, and formed two channels roughly at the same time (the middle picture in figure 2.2). This was again seen in a geometry with electrodes and dielectric moved about 50% further apart. When the dielectric was moved further away at same electrode spacing, the discharge made a channel only through the gas. The same behavior was observed in the whole pressure range.

2.4 Average velocities

The average velocity of the developing discharge was determined from the ratio of the time it takes a discharge to cross the gap between the electrodes and the length of the path it travels. We found the starting time in the following manner: first, we determined the time delay from the trigger signal after which there was 20% chance out of 20 discharges to observe light emission from the discharge. Let us call this time $a$. After that, we determined time $b$, after which there was 80% chance to make such an observation. The starting time was calculated as an arithmetical average of times $a$ and $b$. We did the same for the moment when the ionized channel was completed - we found the delay times where there was 20% and 80% chance to observe a complete channel between the electrodes and calculated their arithmetical average. The length
of the path crossed by the discharge was measured from the photographs of the discharges.

2.4.1 Measuring conditions

Velocities were measured at ten pressures from 0.1 to 1 bar, for three voltage rise rates: 47, 67 and 100 V/ns, and two dielectric materials. Photographs of successive discharges were taken with 5 ns gate time at two trigger frequencies: 1 Hz and 25 Hz. We discovered that the 25 Hz discharges suffered from considerably less jitter, thus making the measurements much more reliable and easier to perform. Error bars at 1 Hz were roughly 5 to 25 times larger than for 25 Hz.

Furthermore, velocities at 1 Hz were 55% to 65% larger than their 25 Hz counterparts at 0.1 bar, with this difference approaching zero as we increase the pressure. This effect can be explained as follows: It has already been shown \cite{38,42,45} that charge remains on the dielectric surface for a long time after a discharge, even for days in cases of very good insulators. The results show that after minutes of waiting time, the leftover charge preserves the profile of the streamers that were involved in its deposition. This means that throughout our experiment, which ever trigger frequency we used, we had leftover charge remaining in the gas volume and on the dielectric surface after every discharge. As the density of the leftover charge will drop with time, operating the experiment at 25 Hz will cause more leftover charge to be present in the gas volume and on the dielectric surface than at some lower trigger frequency. This leftover charge plays a twofold role. First, it serves as a source of free electrons necessary for the initiation of the discharge. More electrons causes smaller statistical lag time, which makes the discharge less prone to jitter and easier to predict. Second, lots of leftover electrons can serve as a shield, screening the applied potential at the charged electrode. Smaller E/N means lower discharge velocities \cite{82}. Both effects were seen in our experiment. The effect of leftover charge was also pondered upon previously \cite{34,40,41,50}.

All measurements were done for 1 Hz as well as for 25 Hz, and all of them showed the same behavior. For the sake of clarity and reliability, we present only the results of the 25 Hz measurements in the rest of this chapter.
2.4.2 Effect of pressure and geometry

We measured the difference in velocities when the discharge travelled through the gas or over the dielectric. Figure 2.3 shows velocities for BK7, constant voltage rise rate of 67 V/ns (10 kV maximum voltage) and two geometries mentioned in table 2.1.

First, it can be seen that the velocities decreased with rising pressure. As pressure rises, the mean free path of electrons is decreased, effectively slowing down the discharge development.

Second, one can observe higher velocities when the discharge formed an ionized channel over the dielectric surface as opposed to when the channel was formed in the gas. This difference can be seen clearly for the geometry (20mm/7mm) that features both ways of the channel’s formation; in this case the two velocities were measured simultaneously. The question is why the propagation over the dielectric surface is faster than through the gas. Many scientists assumed that this is the result of the dielectric properties of the material. A combination of permittivity of the dielectric and accumulated negative charge on its surface was also suggested to be responsible for an increase of the ionization rate on the dielectric surface, that
Part I.

2.4.3 Influence of dielectric material and voltage rise rate

In figure 2.4, we compare average discharge velocities over the dielectric surface for two dielectric materials. The velocities along their surfaces were about the same, even though their relative dielectric constants differ by roughly a factor three. The material with lower $\epsilon_r$ should produce smaller modifications of the electric field in its vicinity, and therefore have a smaller influence on the speed of the discharge. Small differences (with maximum of 40% at 100 mbar) were observed in lower pressures, but the material with the lower dielectric constant (BK7) exhibited higher velocities.

The local electric field is also affected by the appearance of streamers. To find out in which way, we adapted a model, described in detail in the next chapter. It is a 2D fluid model, suitable for simulating nonuniform electric fields. Five species were included in the calculations - argon atom, argon ion, molecular ion, electron and argon metastable at 11.6 eV. We used the model...
to simulate the starting phase of a discharge in argon at 700 mbar, beginning from the gas phase with low initial concentration of charged species, up to the formation of an ionized connection between the electrodes. The fact that this is not a 3D model highly specialized for our experiment gives rise to errors in absolute values of its results. The advantage is that this model can be used to reproduce the whole process from the low initial particle densities, which is typically the case in gasses, until the moment the ionized channel forms between the electrodes. The fact that the model is 2D causes the electric fields at sharp electrode tips and at the streamer heads to be lower than in reality, but it gives correct trends and correctly describes the behaviour of the discharge.

The simulations showed that the tip of the streamer was nearly at the same potential as its origin, the charged electrode. Maximum of 20% drop in potential was observed across the streamer length, just prior to the formation of the connection between the electrodes. This can easily be explained by the fact that a streamer is essentially an ionized, conductive channel. As streamer heads in argon are very narrow (a 5 kV streamer at atmospheric pressure is a fraction of a millimeter wide \[78\]), a high electric field is present in the area around streamer tips, with values that exceed the electric field imposed by electrode potential. Compared to the effects of the space charge, that completely alters the local profile of the electric field, the modifications caused by the dielectric property of the insulating material will have a small impact on streamer velocity along its surface.

Impact ionization of electrode surface by heavy particles in the discharge is one of the processes often considered relevant for fast propagation of discharges. However, it is by orders of magnitude too slow, as the whole ignition process in our experiment takes up to 150 ns.

In this circumstances, one has to consider other sources of electrons that can enable fast streamer propagation. As has been already suggested, leftover charge can play a role in streamer growth \[40,41\]. The desorption theory also predicts extra free electrons near the insulating surface \[50,53,55,57\]. In any case, it has been shown that in non-guided discharges in rare gasses the expansion speed is governed by both drift electrons and free electrons generated by a short-range source in a narrow layer around the channel surface \[59\].

On the other hand, photoemission of electrons from the dielectric surface can be viewed as a mechanism partly responsible for the fast propagation.
Although it still has not been proven, photoemission of electrons from the dielectric surface is a concept proposed quite a few times already \[35\,37\,41\,43\,46\]. The region around the streamer tip is active with different reactions like ionization, excitations and deexcitations of argon atoms. Electron relaxation from the first excited state in argon can result in emission of an 11 eV photon, that would be able to photo-ionize the dielectric surface.

In figure 2.4, one can also notice an increase of velocity with an increase of voltage rise rate. This effect was observed previously by Winands \[83\], and explained by different inception voltages for discharges initiated by voltage pulses of different rise rates. A faster pulse will initiate a discharge at a higher voltage, which will aid the propagation of the discharge. Moreover, the imposed electric field will rise more quickly for a faster rise rate of the voltage pulse, which will increase the velocity of the discharge at a higher rate.

### 2.5 Velocity as a function of relative position of the discharge

A fast iCCD camera and a low-jitter setup allowed us to follow the discharge through every step of its growth. We performed detailed measurements of the position of the discharge tip with respect to elapsed time, to obtain space resolved velocities and possibly gain more insight in the inner workings of the whole discharge development process.

In order to be able to calculate the space resolved velocity, we took photographs of the discharge in 5 or 10 ns steps from the moment the first light from the discharge was observed. Five photographs were taken for each delay time, from which the mean position of the discharge tip was calculated. The tip position was fitted to a second order polynomial with respect to the elapsed time. The agreement was very good in all measurements. Time derivation of the fitted curve gave us the velocity at each position of the discharge tip, and the errors of associated polynomial coefficients gave us the error bars for the velocities.

#### 2.5.1 Effect of the dielectric surface

Figure 2.5 shows measured velocities for different dielectric materials as a function of the relative position of the discharge tip between the electrodes. As pointed out in the last section, discharge velocities over dielectric surfaces were
Surface and volume discharge velocities

Figure 2.5: Space resolved velocities for two dielectric materials. 25 Hz, 30mm/7mm geometry, 700 mbar, 100 V/ns. The discharge formed a conductive channel over the dielectric surface. The velocities are up to 16% higher for the discharge propagating along the BK7 surface than for Al₂O₃, which is consistent with the average velocities at 700 mbar shown in figure 2.4. The position of the connection point depends on pressure.

Unmistakeably larger than discharge velocities in gas volume. They were not constant, but rose as the discharge approached the grounded electrode. As streamers are electrically conductive channels, their tips will be near the same potential as the charged electrode (according to our calculations, there is a maximum of 20% voltage drop across the channel in our experiment). Therefore, as the distance to the grounded electrode decreases, the potential gradient inevitably grows, thus creating higher and higher electric fields at the tip of the streamer.

Note that due to our electrical system (see figure 2.1), the potential over the electrodes increases during the whole discharge development. One can perform a quick calculation of changes in the electric field caused by the increase in voltage for a point-charge, excluding the influence of the discharge movement. For the 100 V/ns case, the potential increases about 20% during the streamer propagation, whereas the streamer velocity increases by 75% (see BK7, figure 2.5).

As for the change in the electric field caused by the discharge tip approaching the grounded electrode, we know that for a simple point-charge model, the
Coulomb force has an inverse quadratic dependence on the distance between two point charges. By combining this simplified point-charge model and the data we gathered in our experiments, we calculated the potential increase to be 125% due to the discharge movement for the 100 V/ns case from figure 2.5. This value is well beyond the velocity increase, but it proves that the effect of the movement of the discharge surpasses the effect of the potential increase at the charged electrode.

In our discharge, the local electric field rapidly grew as the discharge approached the grounded electrode, and as larger $E/N$ translates to higher streamer velocities [82], the discharge speeded up along its path, mainly as a result of its own movement.

However, this is true for all streamer-like discharges, irrespective to their vicinity to a dielectric surface. The fact that our discharges speeded up on their way to the grounded electrode with different accelerations cannot be explained electrostatically or by the fact that the potential of the charged electrode rises in time because this is common in both surface and gas volume discharges. From figure 2.5 it can be deduced that the velocity of the surface discharge either has a stronger dependence on the applied electric field than that of the volume discharge, or that there is another mechanism speeding up its growth. This other mechanism can be anything from local field enhancement by the presence of the dielectric, secondary electron emission from the surface, extra energy provided to the electrons by sheath acceleration, electron detachment from the charged surface by the electric field in the streamer tip, to photoionization of the surface or photo-detachment from the charged surface. The modelling results published by [29] suggest that the main culprit for fast charge development on the dielectric surface is enhanced bulk ionization due to enhancement of the electric field near the dielectric surface, but one should bear in mind that this model was devised for the electrode geometry specific for guided discharges, where the electric field amplification is much greater than in our experiment.

2.5.2 Influence of geometry and pulse rise rate

Figure 2.6 shows velocities for different geometries, as specified in table 2.1. Velocities of the discharge over the dielectric surface were always considerably higher, roughly by a factor two compared to the discharge velocities in the gas volume. This agrees with previously shown results (figure 2.3).
Figure 2.6: Geometry dependence of the velocity of the discharge. 25 Hz, 700 mbar, Al₂O₃, 100 V/ns. Depending on the geometry, the discharge propagated through gas volume, over the dielectric surface or both.

Figure 2.7: Space resolved velocities of the discharge travelling over the dielectric surface as a function of voltage rise rate. Measurements were done at 25 Hz and 400 mbar, for 30mm/7mm geometry with BK7. Dashed lines represent the average velocities with error bands for each of the voltage rise rates, obtained by the method described in the previous section.
Finally, we show the influence of voltage pulse rise rate on discharge velocities. Figure 2.7 shows two effects: first, the average discharge velocity rose with voltage rise rate, as we have already seen in figure 2.4. Second, the change of discharge velocities over time was proportional to the voltage rise rate. The discharges propagated at similar speed at the beginning of the propagation, when the discharge tip was near the anode, but the velocities increased from 20% for 47 V/ns, through 64% for 67 V/ns, to 129% for 100 V/ns by the time the ionized channel was formed between the electrodes. These effects were previously observed and explained by Winands [83].

Two techniques of measuring velocities are compared in the last figure (2.7). Average velocities are 5 to 12 % lower than an average calculated from the space-resolved measurements. This effect is a result of the differences in measurement techniques. Average velocities include the whole development of the discharge, from the moment the first light appears at the charged tip to the time when a conductive channel is completed between the electrodes, including the initial branching of the discharge in gas. The space-resolved velocities refer only to the discharge propagation over the dielectric surface, which is faster than the one in the gas. Therefore, the average discharge velocities will always appear lower than their space-resolved counterparts.

2.6 Conclusions

We examined the initial development of discharges in argon and a pin-pin geometry, and the influence of nearby dielectric materials on the ignition process. We presented three geometry arrangements that represent three modes of forming an ionized channel between the electrodes - in the gas volume between the electrodes, over the dielectric surface or both at the same time. In all three cases, the initial stages of the ignition process showed a tendency of the discharge to propagate towards the dielectric surface, which is a consequence of the shape of the initial potential distribution.

Our velocity measurements revealed higher average speed in low pressures due to higher $E/N$ values and higher voltage pulse rise rates. Results for space resolved velocities showed good agreement with the corresponding average speed, but also revealed that the velocities of discharges that propagate over the dielectric surface are not constant. In fact, the propagation speed increases as the discharge approaches the grounded electrode. In that time,
two effects take place: first, the potential at the charged electrode increases. Second, the distance between the discharge tip and the grounded electrode decreases, causing a steeper potential gradient in front of the discharge tip. Both effects cause the discharge to speed up.

We found the permittivity properties of the dielectric materials to have little influence on the velocities of the discharges travelling over the dielectric surface. The appearance of space charge causes high electric field at the discharge tip, that takes over the potential distribution in the system, minimizing the effect of the dielectric material.

All experiments showed that the propagation over the dielectric surface is faster than through the gas. This effect may be a result of the presence of charge on the dielectric surface, leftover from previous discharges. On the other hand, in line with many previous works, a possible explanation is associated with photoemission of electrons from the dielectric surface, that would effectively increase the ionization rate in front of the streamer head that travels over the dielectric surface, thus speeding up the discharge. The theory of desorption flashover can also explain the effects we observed.

The determined increase of the discharge growth velocity as it travels along the dielectric surface is a result that is greatly relying on the particular combination of geometry and voltage levels used in the experiments. We do not expect the same results in pin-plate or pin-gas geometry. When comparing the results presented in this chapter with velocity measurements in other experimental conditions, one must take great care to include the comparison of the experimental geometry and the voltage. If this is not done, the only result that can be compared is that the growth velocity is greater for discharges that form on the dielectric surface than for the ones forming in the gas under same potential difference.
Part II

Simulations of the pulsed breakdown process
The role of metastables in the formation of an argon discharge in a two-pin geometry

Abstract. Breakdown processes in gas are a versatile research topic. Numerous processes play more or less important roles in discharge formation, strongly depending on the gas mixture, the electrode configuration, the applied electric field, the size of the geometry, even on the structures surrounding the active volume where the breakdown takes place. We focus our research on breakdown process in argon at 700 mbar, in a pin-pin electrode geometry, with increasing positive voltage at the active electrode. The voltage rises by 100 V/ns. We use a two-dimensional fluid model to examine the formation of a charged channel between the electrodes under given conditions. We find that the results describe previous experiments reasonably well. We also explore the role of excited argon atoms at (4s) metastable levels in the breakdown process, and we conclude that the ionization path with an intermediate step containing the metastables does indeed make a notable difference in the breakdown process.
3.1 Introduction

Electrical discharges in gases (gas discharges) are widely used in modern society. They have been studied in different ways - both fundamental as well as practical knowledge has been obtained to satisfy both industrial needs and the needs of the scientific community. Lighting industry drives extensive research efforts in this field, both application-driven and the research into fundamental processes. A lot has been understood thus far, but even more new questions have been raised. In particular, the breakdown process in lamps is still not completely understood. It has been researched and modelled for low-pressure lamps, experimental studies have been carried out for high-pressure lamps and modelling was done for breakdown process in metal-halide lamps with low noble gas pressure.

Modern high intensity discharge (HID) lamps are used in many ways; all applications require high efficacy, good color rendering, and high energy output from a pea-sized volume. For that reason, lamps are filled with noble gas at high pressure (0.1 to 12 bar) and salts. Noble gas provides light during the warm-up phase of the operation and salts take over light emission after they have evaporated. Due to the high gas pressure, these lamps are difficult to ignite: it typically takes a pulse between 5 kV and 20 kV to build a conductive channel in the gas between electrodes, while the latter stage of lamp operation requires only a fraction of that value.

Attempts have been made to lower breakdown voltage in HID lamps. This can be accomplished in several ways. Lay et al. showed that a small amount of Hg can improve HID breakdown characteristics, that is to say, lower breakdown voltage, thanks to the Penning process. Bhoj et al. showed that small admixtures of Xe (5-15 %) in an Ar atmosphere also help lower the breakdown voltage, due to the lower ionization potential of Xe, while the electron energy distribution function (EEDF) is not significantly altered with respect to pure Ar. These modelling efforts have described the ignition process in noble gas pressures ranging from 10 to 90 Torr (13 to 120 mbar), where discharges are glow-like and not constricted. Research in the field of high pressures of noble gasses has been mainly experimental, and it has been shown that, due to high voltages, the criterion for glow to streamer transition is fulfilled and the discharges forming under these conditions are filamentary, streamer-like ionizing channels. Experiments have also shown that the break-
down voltage rises with pressure, and that the speed of propagation of the discharge rises with applied voltage and decreases with increase in pressure.

Recently Wendt et al. [97] qualitatively described the discharge in Xe at 0.1 to 5 bar, at electrode distance of 5 mm. Pulse rise rate was varied, between 10 and 1000 V/ns. In their research, they used a one-dimensional fluid model, with the part where they solved the Poisson equation, the species continuity and energy balance equations. The electron transport and reaction rate coefficients were functions of the local electric field. Starting particle densities were quite low (10^8 m^-3 for electrons and 10^{12} m^-3 for atomic ions), but they corresponded to the particle densities in reality. The model showed an ionization front propagating towards the cathode, its speed and breakdown voltage highly dependent on the pulse rise rate. The electric field at the discharge tip was in the order of magnitude of 10^6 V/m.

The aim of this chapter is to describe by means of computer simulations a high-pressure discharge in argon. We would also like to demonstrate the importance of metastables in near-atmospheric argon discharge, as the ionization paths containing metastable states are sometimes neglected in the models describing the breakdown process [98]. To this end, we characterized the breakdown process between two pin-electrodes, in 700 mbar argon atmosphere. We focused on the breakdown process during a rising voltage profile (the ramp in the rest of the chapter), like the one used for the experiments described in chapter 2. The reference measurements for such a system gave the breakdown voltage of around 14 kV [81], and the discharge speed between 2.5 \times 10^5 and 3 \times 10^5 m/s (chapter 2). We found our results in reasonable agreement with the experiments. Next, we examined the influence of the atomic metastables on the discharge formation. We concluded that even though they did not play the decisive role, the inclusion of the processes of atomic metastable ionization did make a notable difference in the timing of the discharge evolution.

3.2 System under consideration

3.2.1 Geometry

The system under consideration is a model representation of the setup used in the experiments where we measured the speed of discharge in argon (chapter 2). We use a cylindrically symmetric geometry to describe a system of two
electrodes (0.06 mm in diameter, work function of 4.5 eV) in a 700 mbar argon atmosphere at 300 K. The distance between electrode tips is 30 mm. 10 mm of extra space is provided at the sides of the electrodes, in order to diminish the effects of the computational boundaries.

The computational domain consists of $1200 \times 322$ square grid cells, $(0.03 \times 0.03)$ mm$^2$ in size. We found that the optimal ratio between cell sizes in radial and axial direction is around one, even though the discharge propagates in the axial direction. This is due to the fact that the streamer that propagates through the gas volume has a certain width, which should be bigger than one cell size in radial direction. The smallest radii measured in experiments \[82\] were 0.1 to 0.2 mm, so the cell size of 0.03 mm in radial direction should be sufficient. The cell size (therefore the total number of cells) is chosen for optimal output and calculation time, considering the lack of grid refinement in the model.

In the experiment, we used tungsten rod-shaped electrodes, 0.6 mm in diameter. However, in the model, the sharp edges of the electrodes cause effects that do not appear in experiments. In experiments, the discharge in argon at near-atmospheric pressure initiates at the tip of the electrode. Even if the electrode does not have a tip, there is always some asymmetry in the system, for example slight misalignment of the electrodes, or more commonly micro fractures that make the discharge favour one region or one spot on the electrode. The geometry in our model is two-dimensional cylindrically-symmetric, which is why we cannot introduce any asymmetry. The modelled discharge starts at the region with highest electric field, which is at the electrode edge. However, being two-dimensional cylindrically-symmetric, a point at the electrode edge in the model represents a ring at the electrode edge in reality. After such discharge initiation, we get propagation of the discharge in the direction of the externally applied electric field, where the particle densities form a cylinder around the symmetry axis which diverges as it approaches the cathode, instead of a channel with highest density in its center, whose profile does not diverge. This is indeed an artifact which is not observed in experiments. When obtaining the results we show in the next section, we used electrodes whose dimensions are 3 mm in length and just one cell (0.03 mm) in radius.
3.2.2 Voltage shape

The voltage of the following form is applied at the electrodes:

\[
V_{\text{electrode}} = \frac{\partial V}{\partial t} t - I_{\text{electrode}} R_{\text{electrode}} \tag{3.1}
\]

\[
I_{\text{electrode}} = \int \int_{\text{electrode surface}} (j \cdot e_{\perp} - \epsilon \frac{\partial}{\partial t} E \cdot e_{\perp}) d^2S \tag{3.2}
\]

\(\partial V/\partial t\) is the rise rate of the ramp, \(t\) is time, \(I\) is current through the electrode and \(R\) is resistance in series with the electrode, which is always present in experiments. \(j\) is the plasma current density (sum of all the fluxes of the charged species multiplied by the relevant unit of charge). The second term in equation 3.2 is the displacement current. The cathode is connected to ground (\(\partial V/\partial t = 0\) V/ns) with resistance of \(R = 10\ \Omega\), and there is a ramp applied to the anode (\(V_R = \partial V/\partial t = 100\) V/ns). The serial resistance at the anode is set to \(R = 1000\ \Omega\). These values were chosen to accurately describe the experimental conditions (chapter 2).

3.2.3 Input data

The model described in this chapter deals with a pure argon discharge. The plasma which is characterized is not in thermal equilibrium; during the breakdown the mean electron energy can reach several electron volts (eV), while the temperature of ions and neutrals stay close to room temperature. Given the high pressure, low ionization degree and very quick timing (our process develops over about 150 ns), the density and the temperature of the ground state argon atoms can be considered constant. We describe the time evolution of electrons, argon atomic and molecular ions (\(\text{Ar}^+\) and \(\text{Ar}_2^+\)), and argon metastables (\(\text{Ar}^*\)) representing the \((4s)\) atomic metastable states.

The reactions initially included in the model are given in Table 3.2. We included the reactions that are commonly considered in simpler argon models. After careful consideration of results and testing, we concluded that due to very short development time of the discharge (around 150 ns) and low particle densities, the recombination reactions made no difference in the model. As a consequence we decided to present results using a reduced model, which considers only reactions 1-6 in Table 3.2. Rates for excitation and ionization of
Table 3.1: Transport coefficients used by the model

<table>
<thead>
<tr>
<th>Species</th>
<th>$\mu_p$</th>
<th>$D_p$ [Torr cm$^2$ s$^{-1}$]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$f(\epsilon)$</td>
<td>Einstein relation</td>
<td>99</td>
</tr>
<tr>
<td>Ar*</td>
<td>$-$</td>
<td>82.992</td>
<td>100</td>
</tr>
<tr>
<td>Ar$^+$</td>
<td>$f(E/N)$</td>
<td>Einstein relation</td>
<td>99</td>
</tr>
<tr>
<td>Ar$_2^+$</td>
<td>$f(E/N)$</td>
<td>Einstein relation</td>
<td>99</td>
</tr>
</tbody>
</table>

Table 3.2: Reaction coefficients used by the model

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Reaction coefficients $k_r$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$e + Ar \to e + Ar^*$</td>
<td>$f(\epsilon)$</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>$e + Ar^* \to 2 e + Ar^+$</td>
<td>$f(\epsilon)$</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>$e + Ar \to 2 e + Ar^+$</td>
<td>$f(\epsilon)$</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>$Ar^+ + 2 Ar \to Ar_2^+ + Ar$</td>
<td>$2.5 \times 10^{-43} m^6 s^{-1}$</td>
<td>101</td>
</tr>
<tr>
<td>5</td>
<td>$2 Ar^* \to Ar^+ + Ar + e$</td>
<td>$1.2 \times 10^{-15} m^3 s^{-1}$</td>
<td>101</td>
</tr>
<tr>
<td>6</td>
<td>$e + Ar^* \to e + Ar$</td>
<td>$f(\epsilon)$</td>
<td>99</td>
</tr>
<tr>
<td>7</td>
<td>$2 e + Ar^+ \to e + Ar$</td>
<td>$5.4 \times 10^{-39} \times T_e^{-\frac{3}{2}} m^3 s^{-1}$</td>
<td>102</td>
</tr>
<tr>
<td>8</td>
<td>$e + Ar^+ \to Ar + h\nu$</td>
<td>$1 \times 10^{-17} m^3 s^{-1}$</td>
<td>102</td>
</tr>
<tr>
<td>9</td>
<td>Ar$_2^+$ + Ar $\to Ar^+ + 2 Ar$</td>
<td>$2.496 \times 10^{-36} m^3 s^{-1}$</td>
<td>103</td>
</tr>
<tr>
<td>10</td>
<td>$e + Ar_2^+ \to Ar^* + Ar$</td>
<td>$7 \times 10^{-13} (300 K/T_e)^{1/2} m^3 s^{-1}$</td>
<td>101</td>
</tr>
</tbody>
</table>

argon atoms, as well as for collisional deexcitation of the metastable levels were obtained from Bolsig+ [99], as functions of mean electron energy. The amount of metastables in the mixture for Bolsig+ calculations was assumed to be zero. We have tested the model with tables generated for metastable amount equal up to $10^{-4}$ with respect to the amount of ground-state atoms in the gas and obtained exactly the same results. In reality, as will be shown in the next section, the average metastable density in the gas mixture is at least 5 orders of magnitude lower than the neutral gas density. Reaction rates calculated by Bolsig+ and the reaction rate for molecular ion dissociative recombination are given as a function of local mean electron energy. They are shown in figure 3.1. The other reaction coefficients are constant and were taken from the literature.
Figure 3.1: Reaction coefficients for several reactions included in the model, as a function of mean electron energy. See Table 3.2 for description.

3.2.4 Starting conditions

Starting conditions for the model are given in Table 3.3. Starting particle densities are sufficiently low to represent starting particle densities in a gas. We have tested the influence of starting particle densities up to $10^{12}$ m$^{-3}$ for electrons and atomic argon ions. We found that the initial electron density weakly influences the speed of the discharge growth (propagation) up to a value of $10^{12}$ m$^{-3}$: the higher the initial density, the lower the speed of propagation. The difference in maximum speed of the discharge between models with initial electron densities of $10^9$ and $10^{12}$ m$^{-3}$ is 9%.

Table 3.3: Initial particle densities.

<table>
<thead>
<tr>
<th>Species</th>
<th>Initial density $n_p$ [m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>$Ar^*$</td>
<td>0</td>
</tr>
<tr>
<td>$Ar^+$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>$Ar^+_2$</td>
<td>0</td>
</tr>
</tbody>
</table>
3.3 Fluid model

The model used in this study is a part of the Plasimo modelling toolkit [104]. The model was originally created and documented by Hagelaar and Kroesen [105,106] for plasmas in display devices. It has been further developed for many other applications [104]. As far as lighting purposes are concerned, the extensions done for modelling ignition in fluorescent tubes [91,92] were done by van Dijk and Brok. We adapted parts of the model to characterize a breakdown event in a high-pressure system; the details of the model are discussed below.

A fluid model describes a physical system by using balance equations for particles and energy. The balance equation for particle species $p$, in terms of the species density $n_p$, flux $\Gamma_p$ and the source term $S_p$ as a function of time and space is:

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \Gamma_p = S_p$$

(3.3)

The source term $S_p$ depends on the volume reactions included in the model. It consists of positive contributions for reactions in which particles of type $p$ are created, and of negative contributions from the reactions in which the corresponding particles are destroyed.

$$S_p = \sum_r c_{r,p} R_r$$

(3.4)

c_{r,p} is the net stoichiometric coefficient of reaction $r$. It can be expressed as $c_{r,p} = \beta_{r,p} - \alpha_{r,p}$, where $\alpha_{r,p}$ is the stoichiometric number of particles $p$ entering the reaction $r$, and $\beta_{r,p}$ is the stoichiometric number of particles $p$ being produced in the reaction $r$. $R_r$ is the associated reaction rate. This reaction rate is a product of the reaction rate coefficient $k_r$ and densities of the reacting species $n_p$.

$$R_r = k_r \prod_p n_p^{\alpha_{r,p}}$$

(3.5)

The flux density in equation (3.3) is given by the momentum transport equation, approximated by the drift-diffusion equation

$$\Gamma_p = \mu_p E n_p - D_p \nabla n_p$$

(3.6)

The first term is the drift flux density, with the particle mobility $\mu_p$. The sign of the charge of a species determines the sign of the associated mobility.
second term is the diffusive flux density, with as the diffusion coefficient of the species p.

The temperature of the neutral species in the model (namely argon metastables) is assumed to be the same as the temperature of surrounding gas. The ion temperature \( T_i \) is related to the background gas temperature \( T_g \) and to the electric field \( E \) as follows \[107\]:

\[
k_B T_i = k_B T_g + \frac{m_i + m_g}{5m_i + 3m_g} m_g (\mu_i E)^2
\] (3.7)

The ion mobilities \( \mu_{ion} (E/p) \) are given in a form of a look-up table and the diffusion coefficients are calculated according to the Einstein relation:

\[
D_p = \frac{k_B T_p \mu_p}{q_p}
\] (3.8)

\( k_B \) is the Boltzmann constant and \( q_p \) is the charge of the particle of type \( p \). The same assumptions for the temperature do not typically hold for electrons because of their small mass which causes poor energy transfer in electron-neutral collisions. The parameters concerning electrons are instead given as a function of the local mean electron energy; the same holds for the reaction coefficients, because the electrons are considered the most energetic particles in reactions in which they take part. Local mean electron energy is given by the energy balance equation

\[
\frac{\partial (n_\varepsilon)}{\partial t} + \nabla \cdot \Gamma_\varepsilon = -e \Gamma_e \cdot E + S_\varepsilon
\] (3.9)

Electron energy density is related to electron density by \( n_\varepsilon = \varepsilon n_e \). The first term on the right hand side represents the heating by the electric field. The second term is the energy gained or lost in reactions, and is given by

\[
S_\varepsilon = -\sum r c_r \varepsilon_r R_r
\] (3.10)

The summation above is performed only over reactions with electrons as one of the reacting species. The value \( \varepsilon_r \) is the energy gained or lost in reaction \( r \).

The mean energy flux density in equation (3.9) is given by

\[
\Gamma_\varepsilon = \frac{5}{3} \mu_e E n_\varepsilon - \frac{5}{3} D_e \nabla n_\varepsilon
\] (3.11)
The second term in the equation above is the heat conduction flux, proportional to the mean electron energy gradient.

The electron temperature can be related to its energy by \( k_B T_e = (2/3) \bar{\epsilon} \). We use the Einstein relation to calculate the diffusion coefficient for electrons as well.

The electric field in the system is calculated by solving the Poisson equation.

\[
\nabla \cdot \epsilon \nabla \phi = -\nabla \cdot \epsilon E = - \sum_p q_p n_p 
\]

Boundary conditions used in the model have been described in detail by Hagelaar [105,106]. Here we will present them in short. For the boundary conditions for Poisson’s equation, we use the electrode potentials at the electrode edges and homogenous Neumann boundary conditions at the open boundaries and at the symmetry axis. For particle densities \( n_p \) and electron energy density \( n_\epsilon \) we employ homogenous Neumann boundary conditions at open boundaries and at the symmetry axis.

\[
\begin{align*}
\nabla V \cdot e_\perp &= 0 \\
\nabla n_p \cdot e_\perp &= 0 \\
\nabla n_\epsilon \cdot e_\perp &= 0 
\end{align*}
\]

\( e_\perp \) is the outward unit vector normal to the boundary. At the electrode surface we do not define reflection or secondary electron emission coefficients, as secondary electron production is commonly ascribed to the heavy particle impact to the electrode surface. It has been shown [16] that in fast pulsed breakdown, heavy particles do not have sufficient time to move from the place of their creation. The boundary conditions are the same for all species:

\[
\Gamma_p \cdot e_\perp = (2a - 1) \mu n_p E \cdot e_\perp + \frac{1}{2} v_{th} n_p 
\]

\[
a = \begin{cases} 
1 & ; \mu E \cdot e_\perp > 0 \\
0 & ; \mu E \cdot e_\perp \leq 0
\end{cases}
\]

The coefficient \( a \) is set to 1 if the drift velocity of the given species has a component directed toward the boundary, zero otherwise.

The model uses control volume method for solving equations for densities of the species, electron energy density and electrostatic potential. We use a uniform two-dimensional grid with rectangular elements \( \Delta x \) and \( \Delta y \) in size. Each cell is defined as either a part of the plasma region or an electrode element,
Formation of a pulsed argon discharge

in which case we assign voltage to the cell. Poisson and transport equations are solved in the plasma region of the defined grid.

3.4 The breakdown process

In the next two sections we present the results of simulations. First we discuss the simulation of a 700 mbar discharge in argon between two pin electrodes at 3 cm distance; afterwards we analyze the influence of reactions involving argon metastables on the overall process.

3.4.1 Appearance of the discharge

The breakdown process in near-atmospheric pressure argon has been documented and described before [26,82], and the results of our own experimental research is presented in chapter 2. The breakdown process features bright, constricted channels propagating through the gas volume at high velocities. Branching occurs, and the path the discharge takes is straight only in segments between the branching points. However, the general direction of the discharge is always in the direction of the externally applied electric field.

The described appearance differs greatly from the glow-like discharges at lower pressures. The explanation for the narrow channel profile is that at high pressures, the density of the background gas is quite high ($1.7 \times 10^{25}$ m$^{-3}$ in our case of 700 mbar); the creation and destruction processes in the plasma are thereby localized to a small space at the maximum of the reduced electric field. At the beginning of the discharge formation the electric field maximum is at the electrode tip, and during the propagation the maximum is at the discharge tip, due to the space charge in the head of the discharge.

Our model, being 2-D cylindrically symmetric, cannot simulate the branching of the discharge, or its erratic path, as observed in experiments shown in chapter 2 and [82]. We do, however, show the propagation of a thin channel along the direction of the electric field. Figure 3.2 shows a two-dimensional distribution of argon metastable density during the propagation of the discharge. The metastable density profile cannot be directly compared to the experimental observations because in experiments, one observes light emitted from the gas volume, not particle density. However, the light is emitted in radiative recombination or relaxation of excited atoms in plasma, and the light
Part II.

Figure 3.2: \( n_{\text{Ar}^*} \) at different moments during the discharge evolution. The pictures are stretched in vertical direction by factor 2.5, in order to better show the radial profile of the metastable density. Each picture is \((0.96 \text{ mm}) \times (3 \text{ cm})\) in size. Note that the computational space is wider than shown in the figure and that the figures show only one half of the rotationally symmetric argon metastable distribution. The lower horizontal border in each picture is the symmetry axis.

intensity is proportional to the density of the species involved. Visible and near-visible light that comes from relaxation of the neutral atoms is most frequently observed in experiments, which is why we choose to show the density of the metastable atoms.

In figure 3.2 there are two discharge formations growing from electrode tips. At the cathode, there is a glow-like structure of lower particle density. At the anode side, there is first charge accumulation at the electrode tip, followed by fast growth of a thin channel of high particle density, directed towards the cathode. Please, note that the metastable density in the figure is presented in logarithmic scale, in order to better show the details of the discharge formations forming between the electrodes. For the same reason, the ratio of the units of
distance on $x$ and $y$ axis in the figure is not unity; each part of the figure shows a $(30 \text{ mm}) \times (0.96 \text{ mm})$ part of the modelled discharge between electrode tips, and starting from the symmetry axis. In the figure, the discharge speeds up on its way through the gas - an effect observed in the experiments (chapter 2).

### 3.4.2 Discharge evolution in time

Figure 3.2 shows that the channel propagating from the anode reaches the glow-like cloud around the cathode a bit later than 130 ns after the beginning of the simulation. The actual voltage breakdown takes place 134 ns after the beginning of the simulation, at 13.4 kV, as shown in figure 3.3. During the remaining few ns, a high particle density channel is formed in the remaining space between the electrodes close to the cathode tip, and fast charge multiplication takes place until the moment when the current through the anode is high enough to cause a drop in the anode voltage, as predicted by the equation 3.1 and shown in figure 3.3.

Figure 3.3 also shows the average density of particles in the whole computational volume, for all particle types and as a function of time. The average densities in the model depend on the size of the computational volume; even so, the main contributor to the values described above is the ionized channel that propagates through the gas, because densities in the channel are orders of magnitude larger than densities in the other regions of the computational volume. In other words, we can track the evolution of the species in the ionized channel by observing the average particle densities in the whole volume, as a function of time.

During the first 7 ns of the simulation, the electron density stays at the initial value, while the density of atomic ions slightly drops, mainly due to inelastic collisions with the background gas, in which the molecular ions are produced (reaction 4 in Table 3.2). As a result, molecular ion density sharply increases. Argon metastables exhibit a somewhat slower increase, but their density quickly reaches the initial electron density. When the densities of all particle types reach approximately $10^9 \text{ m}^{-3}$, a steep increase in all densities occurs. Same behaviour and timing is observed for every combination of initial particle densities below $10^{12}$ particles per m$^3$, which is the highest initial density which we have tested. During this steep increase, particle build-up takes place at the electrode tips. During this time a streamer has not yet begun to form.
Figure 3.3: Particle densities averaged through the whole computational volume, as a function of time. ‘−’ shows electron density, ‘−−’ is Ar\(^+\) density, ‘···’ is Ar\(_2^+\) density, and ‘−·−’ refers to Ar\(^*\) density. The left vertical axis refers to the anode voltage, shown in the graph in (green) −·− line. The voltage rises linearly in time, with 100 V/ns. We define breakdown time as the moment when the anode voltage starts to drop because of the increase in current, according to equation (3.1).

At the end of the steep increase, at roughly 15 ns after the beginning of the simulation, the atomic ion density is about 4.7 times larger than the electron density, the molecular ion is the lowest of the four at half the level of the electron density and the metastables are the most dense at 10 times the level of electrons. Around this time, a fast narrow channel starts to form. The increase in particle densities continues to be exponential, but much slower.

All particle densities show further increase with time. The metastables remain the most dense species in the computational volume throughout the simulation. Densities of both ion species are at roughly the same level for most of the discharge propagation. Shortly before the breakdown moment, electron and atomic ion densities show a slightly faster increase. We define the breakdown moment as the instance when the anode voltage starts to drop because of the increase in current, according to equation (3.1). With the given resistance parameters in the model (see section III for details), the anode
voltage starts to drop when the anode current reaches around 0.5 A.

Figure 3.2 shows that the metastable density is highest at the symmetry axis, along which the discharge propagates. This is true for all particle species in the model. Densities of all particle types along the symmetry axis are shown in figures 3.4-3.7 for various points in time. Even though the metastables are the most dense species in the computational volume as a whole, electrons and atomic ions have the highest density at the symmetry axis, along the axis of the discharge. This means that the metastables are more diffuse around the charged channel than the electrons and atomic ions. The same is valid for molecular ions.

There is a sharp increase in particle density at the discharge tip in all four graphs, as expected, and the density remains roughly constant throughout the body of the channel. Electron density shows sharp fall near the cathode at the beginning of the discharge formation. This is due to initial drift of electrons away from the cathode tip. A closer look at the densities at the discharge tip reveals additional differences in density distribution for the four species: while electron and atomic ions densities exhibit a sharp “corner” at the tip of the discharge, the densities of the other two species are more rounded, which is especially true for the molecular ions. From this we can conclude that the positive net charge at the tip of the streamer is largely contributed to by the atomic ions, even though the molecular ions do play a significant role in the chemistry of the whole discharge formation.

The positive net charge at the discharge tip causes a high peak in the axial electric field in front of the streamer tip. The axial component of the electric field along the symmetry axis is shown in figure 3.8.

3.5 Role of the metastables

Figure 3.3 showed that the average density of argon metastables in the model rises above the level of any other species. Figures 3.4-3.7 show that the density of the metastable argon atoms in the charged channel is not negligible. However, the role of the metastables in discharge formation is often neglected. Here we would like to show their importance in the breakdown process.

To that end, we made a simple adaptation of our standard model described in the previous section. We removed the two ionization reactions that convert the argon metastables to atomic ions (reactions 2 and 5 from the Table of
Figure 3.4: Electron density at the symmetry axis, as a function of time. Position at the $x$-axis indicates the gap between the electrodes: the anode is at position zero, the cathode is at 3 cm. Each line represents electron density at a given time in the discharge formation; lines are drawn 5 ns apart and start at 5 ns after the beginning of the simulation. The profile progresses towards the cathode as the time increases, which indicates development of a charged channel.

Figure 3.5: Argon ion density at the symmetry axis, as a function of time, similar to electron density in previous figure. Each line represents ion density at a given time in the discharge formation; lines are drawn 5 ns apart and start at 5 ns after the beginning of the simulation.
**Figure 3.6:** Molecular argon ion density at the symmetry axis, as a function of time. Each line represents ion density at a given time in the discharge formation; lines are drawn 5 ns apart and start at 5 ns after the beginning of the simulation.

**Figure 3.7:** Argon metastable density at symmetry axis, as a function of time. Each line represents metastable density at a given time in the discharge formation; lines are drawn 5 ns apart and start at 5 ns after the beginning of the simulation.
Part II.

Figure 3.8: Axial component of the electric field, at the symmetry axis, for different points in time during the discharge evolution. Position at the $x$-axis indicates the gap between the electrodes: the anode is at position zero, the cathode is at 3 cm. Each line represents electron density at a given time in the discharge formation; lines are drawn 10 ns apart. The peaks are caused by net charge at the streamer tip. The axial electric field strength at the peak increases with time, and the position of the peak moves towards the cathode, at increasing speed. This is in agreement with what was observed in experiments.

reactions 3.2), while leaving everything else the same. Argon metastables are still created in the model by excitation of the ground-state atoms and recombination of the molecular ions, and they still relax back to the ground state by inelastic collisions with electrons.

3.5.1 Effect on the density profiles

Figures 3.9 – 3.12 show the average particle densities as a function of time, for all four species, and compared to the densities in the standard model. The figures show that the breakdown moment in the adapted model comes approximately 41 ns later than the breakdown in the standard model; this also means that the breakdown voltage is roughly 4.1 kV higher in the model without $\text{Ar}^* \rightarrow \text{Ar}^+$ reactions (breakdown occurs at 17.5 kV). 41 ns is quite a large difference within the timescales we are considering: the discharge in the adapted model takes about 31% more time to develop than the discharge in the standard model.
Figure 3.9: Average electron density as a function of time, for two different simulations. Solid curve — denotes the electron density in the standard model, and the dashed curve —— shows the average density in the simulation without ionization of argon metastables. Curves stop at respective breakdown moments. Notice that model without $\text{Ar}^+ \rightarrow \text{Ar}^+$ reactions takes longer to breakdown, which suggests lower speed of the propagation of the discharge.

Figure 3.10: Average atomic ion density as a function of time, for two different simulations. Solid curve — denotes the atomic ion density in the standard model, and the dashed curve —— shows the average density in the simulation without ionization of argon metastables. Curves stop at respective breakdown moments.
Figure 3.11: Average molecular ion density as a function of time, for two different simulations. Solid curve — denotes the molecular ion density in the standard model, and the dashed curve — shows the average density in the simulation without ionization of argon metastables. Curves stop at respective breakdown moments.

Figure 3.12: Average metastable density as a function of time, for two different simulations. Solid curve — denotes the metastable density in the standard model, and the dashed curve — shows the average density in the simulation without ionization of argon metastables. Curves stop at respective breakdown moments.
Figure 3.13: Electron density profile along the symmetry axis in a simulation without $\text{Ar}^* \rightarrow \text{Ar}^+$ reactions. Position at the $x$-axis indicates the gap between the electrodes: the anode is at position zero, the cathode is at 3 cm. Each line represents electron density at a given time in the discharge formation; lines are drawn 5 ns apart and start at 5 ns after the beginning of the simulation. The profile progresses towards the cathode as the time increases, which indicates development of a charged channel.

Figure 3.14: $\text{Ar}$ ion density profile along the symmetry axis in a simulation without $\text{Ar}^* \rightarrow \text{Ar}^+$ reactions. Each line represents argon ion density at a given time in the discharge formation; lines are drawn 5 ns apart and start at 5 ns after the beginning of the simulation. The profile progresses towards the cathode as the time increases, which indicates development of a charged channel.
Surprisingly, the evolution of the density of argon metastables is almost the same for the two models. However, electron and atomic ion densities are quite different in the two simulations: a steeper increase with time can be observed in average electron and \( \text{Ar}^+ \) densities in the standard model. The density profile of \( \text{Ar}_2^+ \) ions is slightly lower in the adapted model; the main production channel for this particle type is in collisions of atomic ions and background gas (see Table 3.2), so the decrease in the adapted model is mainly the result of atomic ion density decrease.

Given the effect the removal of \( \text{Ar}^* \rightarrow \text{Ar}^+ \) reactions has on average electron and \( \text{Ar}^+ \) densities, we expect an impact on density profiles along the symmetry axis for the same species. Figures 3.13 and 3.14 show the behaviour of the electron and atomic ion densities in the charged channel, as a function of time. In quite the same manner as in the standard model, steep rise in densities are present at the tip of the charged channel propagating between the electrodes. Electron density stays within the same order of magnitude throughout the channel, like in the standard model. The main effect of the adapted model is that the peak value of electron density is one order of magnitude lower than in the standard model. The \( \text{Ar}^+ \) density profile also shows peak values one order of magnitude lower than in the standard model, but also a significant decrease in density throughout the charged channel, roughly two orders of magnitude for a channel 145 ns after the beginning of the simulation.

### 3.5.2 Speed of the discharge

Figure 3.15 shows the velocities of the discharges in the two simulations, as a function of position in the discharge gap. The velocities were calculated from the positions of the discharge tip as a function of time. For the purposes of this calculation we define the discharge tip as the position of the peak of the axial component of the electric field, resulting from the net charge at the head of the charged channel. Velocity is calculated as the first time derivative of the peak position. Both velocities rise with time, but the maximum velocity of the discharge in the standard model is 27% higher than that of the discharge in the model without ionization of argon metastables.

The experiments done under similar conditions (chapter 2) have shown that the discharge velocities increase on their way through the gas, but the increase observed in experiments was much slower than the one obtained by both simulations: the velocity in the experiment increases from \( 2.3 \times 10^5 \) m/s at 0.4 cm
from the anode to $3 \times 10^5$ m/s at 2.4 cm from the anode. One must remember that the experimentally determined velocities were obtained from fast photography measurements of the discharge, in visible and near visible region. As stated before in this chapter, what we observe in the experiments is light emitted mainly from the excited argon atoms that relax to lower atomic states. In experiments, we cannot determine the position of the peak net-charge density. On the other hand, in our model we cannot calculate the position in the channel where there is enough visible light emitted for an iCCD camera to register. This is one of the reasons why the velocity profile along the discharge path are not the same in experiment and in the model. Another probable reason for the discrepancy between the modelled and the measured velocity is that in experiments, it is nearly impossible to do measurements in pure gas. Experiments in pure gasses typically contain traces of nitrogen and oxygen, and it has already been established by Aleksandrov et al [25] that even very small amounts of oxygen in the discharge changes the dynamics of discharge development, drastically reduces the conductivity of the streamer channel and increases the average electric field required to bridge the discharge gap by a streamer. The proposed mechanism for this effect was quenching of excited argon atoms by oxygen molecules, which leads to the deceleration of two-step ionization in the streamer channel in argon and slowing down of discharge growth.
3.6 Discussion and conclusions

In this study, we modelled the pre-breakdown events in 700 mbar argon, using a two-dimensional fluid model. Our aim was to make an overview of the processes that take place during the initiation and propagation of a high-pressure argon discharge, and to determine the role of atomic metastables in the breakdown process.

3.6.1 Discharge appearance

Experiments have shown that the discharge in 700 mbar argon forms thin channels that propagate from anode to cathode at high velocities, as shown in chapter 2 and [82]. The breakdown voltage for the conditions we simulated were measured at 14 kV [81]. We show the propagation of the discharge as calculated by our model. The discharge propagates from the anode towards the cathode in a narrow, charged channel with a positive net charge at its tip. The net charge is a result of charge separation in the head of the channel, and it causes a high peak in the electric field. There is a glow-like formation growing around the cathode tip, as previously observed by [82] and shown in chapter 2 with particle densities orders of magnitude lower than in the propagating channel.

3.6.2 Propagation mechanism

We have not implemented photoionization in our model; the discharge forms and grows solely due to background ionization. We start with uniform electron density of $10^9 \text{ m}^{-3}$. At the cathode side, during the initiation stage of the discharge development, the electrons drift away from the electrode tip, causing a sharp drop of the electron density, as shown in figures 3.4 and 3.13. At the anode side, charge multiplication and accumulation take place and the accumulated charge modifies the electric field at the tip, causing the electrons around the electric field peak to gain energy and engage in ionization processes. As a result, the discharge starts growing in the direction of the cathode, driven by the high electric field peak at its tip.
3.6.3 Discharge velocity

Growth velocity of the discharge increases in time, like observed in the experiments presented in chapter 2. The increase in discharge velocity is a direct consequence of the increase of electric field strength at the discharge tip, and there are two mechanisms responsible for the increase of electric field:

1. High electric field causes sharp increase in local ionization rates by electron impact at the discharge tip, which follows from Table of reactions 3.2 and reaction coefficients in figure 3.1. High ionization rates cause further increase in particle densities, higher net charge at the discharge tip, and thus further increase of the electric field. This, in turn, facilitates further increase in ionization, higher electric field and so on.

2. The simulation involves the potential at the anode which is rising at 100 V/ns. This causes additional increase of the electric field.

The two mechanisms work toward higher ionization rates at the discharge tip and increase in discharge speed. One could say that after the inception, the discharge pushes itself forward by causing favourable conditions for ionization processes at its tip.

3.6.4 Effect of processes involving atomic metastables

Figures featuring particle densities in the standard model show that the density of argon metastables is quite high in the charged channel, and the highest when it is averaged over the whole computational volume. Given this high density, we wanted to test the importance of argon metastables in the discharge formation. The processes that ionize argon metastables were taken out of the model, and the results of the adapted model were compared to the standard simulation. Averaged over the whole volume, the metastable and molecular ion densities are almost the same in the two simulations, even though we expected the metastable density to be visibly affected by the adaptation. Careful consideration reveals that the process that collisionally de-excites the metastable atoms back to the ground state is the most efficient processes at low electron energies in the model (see Table 3.2 and figure 3.1), which could explain the lack of extra metastables in the adapted model, where Ar* are not used to produce atomic ions. The effect is, however, visible in electron and atomic ion...
densities, which are lower in the adapted model. This is due to the fact that, in the adapted model, atomic ions are no longer produced from the metastable atoms.

In addition, the discharge in the adapted model took 31% more time to reach breakdown; this also shows in its velocity. The speed of the propagating discharge in the standard model is roughly twice as high as the speed of the discharge in the adapted model. The mean value of velocity obtained in the standard model with $\text{Ar}^* \rightarrow \text{Ar}^+$ reactions is comparable to the velocity obtained in experiments.

The significant difference in particle densities and the discharge speed in the two simulations leads to the conclusion that the metastable levels are indeed an important step in the ionization process in near-atmospheric pressure argon. This ionization path is responsible for an order-of-magnitude increase in electron and atomic ion densities at the discharge axis and for a 27% increase of the maximum propagation speed.

### 3.6.5 Outlook

The model predicts the discharge behaviour quite accurately, but there is room for improvements. First, there is a problem with the size of computational cells in the model. If the cells are too big in the direction of the discharge propagation (growth), the streamer head is not properly described. For example, errors in the electric field strength can easily occur. On the other hand, if the computational cells are too big in the direction perpendicular to the propagation of the discharge, the charged channel will be too wide, or the radial profile of the channel will be poorly described, and the discharge will again not be properly characterized. An implementation of local dynamical grid refinement, which is a technique already implemented in many simulations, would solve our problem of cell size, while keeping the requirements on the computer memory and computational time at a reasonable level.

The second improvement we would suggest is to describe the electrodes in an analytical way, instead of assigning them grid cells. This is a technique already used by Celestin et al. [108]. In this way we would avoid the artificial enhancement of electric field at rough corners, which are not present in reality. These artificial electric field peaks can cause side discharges to appear at electrode tips, that would not have been there if the electrode surface was
smooth. One can rightfully argue that the side discharges appear in reality as well, but in a cylindrically symmetric geometry of our model, side discharges are really "umbrella-like" structures, rather than thin ionized channels. This technique of implementing physical boundaries in an analytical way could also be considered for implementation of dielectric boundaries in the model.

One could argue that the chemistry used in the model is too simple to conclusively show the importance of \(4s\) metastable states in development of a near-atmospheric pressure argon discharge. We did consider the possible additions to the chemistry. Consideration of various recombination processes lead us to the conclusion that in the short time frame and low densities in which our discharge develops, the recombination processes play no role in the discharge formation. Additional processes of metastable ionization, such as metastable-metastable associative collisional ionization, could make a slight difference in the metastable and ion densities; however, this would not change the overall conclusion that the ionization path of argon atoms using metastables as an intermediate step does make a notable difference in the modelled breakdown process. If anything, the extra ions produced via this additional process of metastable ionization would make our point even clearer. A possible improvement to the chemistry in our model would be the addition of another excited species, which would represent the \(4p\) and higher excited states in argon. In this way we could couple higher excited argon atoms in the model with other species and more correctly determine the influence of excited species on the discharge formation.

3.6.6 Conclusions

In conclusion, this chapter summarizes results of a two-dimensional fluid model of a discharge in 700 mbar argon. We used a two-pin geometry and a ramp at the anode to describe the initiation and growth of the discharge. The results of the model are in good agreement with the experiments previously performed. We have also demonstrated the importance of the role of argon atoms in metastable \(4s\) states during the breakdown process.
Part III

AC-driven breakdown processes
Introduction

Electrical breakdown in gasses driven by high-frequency AC voltage is a broad domain of interest, connecting research topics originating from the need for fundamental knowledge in various industrial branches. To name a few, knowledge on partial discharges was used in the production of circuit boards and similar systems based on high-power semiconductors [109]; the damage caused by surface discharges was the reason and the motivation for the research. Later, glow discharges created under atmospheric pressure using AC voltage found their use in material processing [110–112]. Also, both volume and surface AC discharges that occur in partial vacuum are of particular interest for aerospace insulating technology and power devices operating in space [113]. The lighting industry focuses on AC discharges in near-atmospheric pressure noble gasses with an admixture of mercury when trying to achieve two important goals: one, to design ignition concepts for high-frequency operated lamps [114], and two, to lower the ignition voltage of lamps [26].

There are clear distinctions between different frequency ranges; in low frequency and high enough voltage, breakdown or partial discharges occur in every voltage cycle. Increasing the frequency for the same pressure, gas type and gap length causes the discharge to take more than one cycle to form. The breakdown processes in high frequencies, in our case any frequency above 10 kHz, can again be divided into several classes; the combination of frequency, gap length and pressure for a single gas defines the relative significance of different effects in the whole breakdown process. For example, for low enough frequency and short enough gap, electron losses are significant and drift-related; increase

The introduction to this part of the thesis has been accepted for publication in a slightly altered form to Journal of Physics D: Applied Physics as part of research articles AC breakdown in near-atmospheric pressure noble gasses: I. Experiments and II. Simulations.
of frequency or gap length causes less drift-related losses and a slow transition into a mode where electron losses are diffusion driven. As a consequence, on the lower end of the high-frequency range, heavy particles are expected to play a more important role than on the high end.

The AC breakdown process at frequencies covering three orders of magnitude between 100 kHz and 100 MHz was described in [9] mostly for low pressures and with the accent on frequencies above 1 MHz. One of the most evident effects when using high-frequency AC instead of pulsed or DC voltage is that the high-frequency AC breakdown requires as much as 50% lower voltage. The explanation offered involves accumulation of the heavy charge in the gap between the electrodes, due to their inability to drift and be lost as current in one half of a voltage cycle. It was proposed that the accumulation of the charge leads to field distortion in the gap and to lowering of the threshold voltage needed for breakdown below the pulsed value. Further increase in frequency, according to [9], complicates the mechanism further due to the lowering of the amplitude of the oscillations of electrons in the electrode gap. The work of Hale [115] in very low pressures and at frequencies above 5 MHz is mentioned in particular for his theory where the breakdown occurs when the electric field and the frequency are such that an electron acquires the ionizing energy at the end of one mean free path length. His calculations described the experimental results in very low pressures quite accurately.

Later observations of the lowering of the threshold voltage when switching to high-frequency AC voltage [26,109,114], and also as the frequency was increased, brought on again the same theories and possible explanations afore proposed by Meek and Craggs [9]. For high frequencies it was argued that the electron drift losses were lowered, which caused a more favourable ratio between electron production and loss [110,112]. As an alternative, in the lower frequency range between 50 and 200 kHz described in [113], the increased charge production and resulting lower threshold voltage was explained by the accumulation of heavy charges in the electrode gap, which in turn create a field distortion and trigger a streamer-like discharge formation.

In this part of the thesis, we present the breakdown process in the 100 kHz frequency range (60 kHz - 1 MHz). Our aim is to examine features of AC-driven discharge in noble gasses. Chapter 4 presents the experimental results of the research done in the frequency range between 60 kHz and 1 MHz in argon and xenon at near-atmospheric pressure. The experiments were performed using 70W Philips high intensity discharge (HID) lamp burners. The electrode gaps
in the experiments were either 4 or 7 mm, and this particular combination of gas pressure, electrode gap and driving frequency positioned our experimental conditions in the high-frequency range where the electron losses were high and drift-dominated. We described the appearance of the discharge, which was found to develop over several voltage cycles. The ionized channel to cross the electrode gap formed in different ways for different frequencies - in the very last part of the last voltage cycle before breakdown in 60 kHz, to several cycles at 1 MHz. We show that the threshold voltage needed for breakdown was decreasing with the increase in the driving frequency, which is a phenomenon that cannot be explained in a satisfactory manner using the already proposed theories [9]. We also comment on the influence of the UV irradiation and $^{85}$Kr used on occasion during the breakdown process.

The aim of chapter 5 is to characterize high-frequency AC breakdown events in a noble gas by means of computer simulations, in the range where most other work on the subject has been experimental [26, 109–113]. We show the results of the simulations done in 0.7 bar argon, in a pin-pin geometry, using high-frequency AC driving voltage. We vary the frequency between 60 kHz and 1 MHz, with an electrode gap of 7 mm, to reproduce as accurately as possible the experimental conditions in the work presented in chapter 4. The simulations show an agreement with the experiment regarding the value for the breakdown voltage, the appearance of the discharge and the behaviour of the threshold voltage for breakdown as a function of frequency. In addition, we show the relative significance of the secondary electron emission from the electrode surface for various heavy species.

Chapter 6 deals with the lag times in the breakdown processes in the experiments described in chapter 4. We show that the statistical lag times are much longer than the formative ones and we give the data on the measured statistical lag times. The compliance with present theories is also examined.
AC breakdown in near-atmospheric pressure noble gasses: I. Experiments

Abstract. AC-driven breakdown processes have been explored much less than the pulsed or DC breakdown, even though they have possible applications in industry. This chapter focuses on the frequency range between 60 kHz and 1 MHz, at a pin-pin electrode geometry and gap lengths of 4 or 7 mm. The breakdown process was examined in argon and xenon at 0.3 and 0.7 bar. We used electrical and optical measurements to characterize the breakdown process, to observe the influence of frequency change and the effect of ignition enhancers - UV irradiation and radioactive material.
4.1 Experimental arrangement

![Diagram of lamp burner and voltage form](image)

**Figure 4.1**: Schematic representation of the lamp burner is shown on top, while the shape of the voltage form used for the experiments is shown below. We used Philips 70W HID burners made of YAG, filled with argon or xenon and equipped with two simple rod-shaped tungsten electrodes.

We adapted the experimental setup used by Beckers et al, described in [26]. The experiments were performed on HID lamps filled with near-atmospheric pressure noble gas. Schematics of the lamps are given in figure 4.1. The chosen geometry was that of the Philips 70W HID burner as used in metal-halide lamps made of YAG (Yttrium Aluminium Garnet). This material was chosen for its transparency and dielectric properties ($\epsilon_r = 11.7$). HID burners are usually made of PCA (Polycrystalline Alumina). While the dielectric constant of PCA is similar to that of YAG, this material is translucent but not transparent, which makes optical measurements impossible. We used rod-shaped tungsten electrodes with a diameter 0.6 mm. The electrodes were made by cutting or breaking a longer piece of tungsten wire, to get the $\pi/2$ angle at the edge. The electrode edges did not receive any special treatment, they were not specially
sharpened or blunted. The distance between the electrode tips was either 4 or 7 mm. The volume of the lamp burners was $3.6 \times 10^{-7}$ m$^3$.

The lamps were positioned horizontally, suspended in air as far away as possible from metallic surfaces - the metallic optical rail and the UV lamp holder. The distance from the nearest metallic surface was about 15 cm.

The lamps were filled in noble gas atmosphere. We used Ar and Xe at 0.3 and 0.7 bar as filling gasses. We also had the opportunity to examine the influence of radioactive materials on the breakdown characteristics; to this end 2.5 MBq/L of $^{85}$Kr was used in a separate set of argon filled lamps. The amount of $^{85}$Kr was measured at atmospheric pressure. It is therefore necessary to scale it with pressure when making estimates for different lamps used in the experiments. One more advantage when using lamps for experiments is that we were able to experiment in more than one lamp per type (a ‘type’ is a particular combination of gas, pressure and the gap between the electrodes), thus reducing the possibility of the results being influenced by a bad set of electrodes, impurities or an error in the lamp filling procedure. Table 4.1 shows the list of lamp types used for the experiments.

Some of the measurements were done with UV irradiation which completely
Part III.

Table 4.1: Lamp types used in the experiments. By ‘lamp type’ we denote a specific combination of gas, pressure, and the gap between the electrodes.

<table>
<thead>
<tr>
<th>Gas type</th>
<th>Pressure [bar]</th>
<th>Electrode gap [mm]</th>
<th>number of available lamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
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<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5</td>
</tr>
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<td>0.7</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Xe</td>
<td>0.3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>4</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Ar + $^{85}$Kr</td>
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<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
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<td>7</td>
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</tr>
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flooded the test lamp. As a UV source we used a Philips TUV 4 W lamp, which produces a narrow emission line at 254 nm. The UV source was kept at a constant distance of 20 cm from the test lamp.

The AC signal employed for the experiments was made using a combination of three function generators. Their respective roles are depicted in figure 4.2. The first function generator (FG 1) provided a pulse that was used both to trigger FG 2 and FG 3 and to determine the duration of the sine signal coming from the FG 3. The second function generator generated a linearly increasing signal, of which the slope could be changed; this signal was used by FG 3 to modulate the amplitude of a sine-shape signal at the desired frequency. The resulting AC signal was a sine of linearly rising amplitude, as pictured in figure 4.1. The experiments were performed in the frequency range between 60 kHz and 1 MHz, and the amplitude (peak) slope was varied between 10 and 1280 V/ms.

For amplifying the AC signal, two AC amplifiers were used, depending on the frequency range. The first one (Spitzenberger power amplifier Viechtach EV 600/C u.G) was used in the frequency range from 60 kHz to 200 kHz; from
200 kHz to 1 MHz we used the ‘AR Worldwide’ 800A3 AC amplifier with variable output impedance. We used a transformer coil after the AC amplifiers to additionally increase the voltage. Two different coils were used in the experiments; one for measurements performed between 60 and 600 kHz and the other one for 500 kHz to 1 MHz. There was some overlap in measurements (500-600 kHz), which was used to validate the measurements done with different coils.

For electrical measurements, we used a Rogowski coil and a high voltage probe. As can be seen in figure 4.2, the output of the Rogowski coil was fed to a current limiter (CL). This is a device, home-made in Philips Lighting, which is used to modify the signal as a function of the input current. The CL was fed the trigger signal provided from FG 1 and transmitted it further as long as the current detected at the input was below the given limit. When the current reached the given limit (i.e. when the breakdown occurred), the device stopped transmitting the signal from FG 1, effectively cutting off the power fed to the lamp. In this way it was ensured that the lamps did not burn for more than a few µs after the breakdown took place. Consequently, we never reached the thermionic emission stage. The experiment repetition frequency was 0.1 Hz, which was sufficiently low to ensure the same starting conditions for every new breakdown process, given that the lamps were filled with noble gas only (no salts or mercury) and that they were not allowed to burn. The average breakdown voltage did not change with further decrease of the experiment repetition frequency.

Breakdown voltages were measured for 11 frequencies between 60 kHz and 1 MHz, at a slope of 100 V/ms. Unfortunately, it was not possible to collect all the data for all the lamp types because of the limitations of the equipment. For example, we could not perform the breakdown voltage measurements for unassisted breakdown in 0.7 bar xenon at frequencies above 500 kHz, because the voltage amplification system could not provide a sine voltage of linearly rising amplitude higher than 5 kV. By unassisted breakdown we wish to denote the breakdown processes which were not aided in any way, which means that we did not use UV or radioactive enhancers. Ten breakdown voltage measurements were performed for each lamp in table 4.1 and for each data point. The average values and the standard deviations were calculated for each lamp, and subsequently for each lamp type. The data points in the graphs represent the average values and the standard deviations for the corresponding lamp type.

For optical measurements two cameras were used. The first one, the Prince-
ton Instruments PiMax:512RB with a $512 \times 512$ pixel CCD array, was used for imaging of 60 and 220 kHz discharges. The second one, the Princeton Instruments UNIGEN II filmless GEN III iCCD camera with a $1024 \times 1024$ pixel CCD array, was used for imaging of 400 and 800 kHz discharges. The photographs were taken for the voltages with 320 V/ms amplitude slope. The camera was triggered by the voltage taken at the active electrode of the lamp. The *active electrode* was the one the voltage was brought to, in contrast with the other, grounded electrode. Gate widths were typically 100 ns for detailed discharge tracking and 1, 5 or 10 voltage cycles for more general observations. The optical measurements were performed only on UV-irradiated lamps because in that case we had lower jitter in the system. The jitter was mainly caused by the lamps themselves, not by the electrical circuitry. Even in these conditions it was often impossible to track the discharge development in 100 ns increments.

### 4.2 Results

In order to avoid any confusion, first we would like to explain the term *breakdown* as used in the text. The *breakdown process* is a set of gradual changes in the gas through a series of states, during which parts of the gas become ionized and a charged channel that bridges the gap between the electrode tips is formed. The breakdown process ends at the *breakdown moment*, which is a particular point in time manifested by a voltage drop across the electrode gap, due to the sudden drop of resistivity of the highly ionized channel that formed between the electrode tips. *Breakdown voltage* is the voltage amplitude at the active electrode at the breakdown moment. The schematic representation of the breakdown moment as observed in our experiments is shown in figure 4.3. In some places in the text the word *ignition* is used as a synonym for breakdown. In lighting research *ignition* is sometimes regarded as the event that encompasses breakdown, take-over and glow-to-arc transition, but we limit our research to the discharge development before and including the breakdown moment.

The voltage amplitude as shown in figure 4.3 appears to be constant, while we claim to have performed experiments with a linearly rising voltage amplitude slope. In fact, the amplitude is linearly rising in the experiments and we are always starting with initial amplitude of zero volts. However, the slope
is slow, and the formative time of the discharge is very small compared to the slope, as is reported in the following subsection. The discharge formation happens only within the last few voltage cycles before the breakdown moment. Consequently, the increase of voltage amplitude during the formation time does not exceed a few tens of volts, which amounts to a few percent of the voltage amplitude at the breakdown moment.

4.2.1 Gas type

The goal of this research was to examine the influence of frequency, UV irradiation and presence of radioactive materials on breakdown parameters in noble gasses often used in the lighting technology - argon and xenon. Qualitatively, the discharges in the two gasses showed a very similar behaviour with respect to main research parameters. However, as expected, a clear influence of gas type on the measured breakdown voltage and the duration of the breakdown process was found.

The difference in breakdown voltage can be seen in figure 4.4, which shows the results for the frequency range from 200 kHz to 1 MHz for 0.7 bar discharges. Comparison of the breakdown voltages of all measured UV-assisted
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**Figure 4.4:** Breakdown voltages for 0.7 bar argon and xenon discharges, under UV irradiation. We can see the influence of the voltage frequency, but also the effect of the gas. The bars, however small, represent one sigma standard deviation from the mean value. Measurements were done using two transformer coils for passive amplification, one at 200 - 600 kHz and one at 500 kHz - 1 MHz. The overlapping measurements in the graph were performed in order to confirm that the values on the edges of the frequency ranges were correct.

ignitions shows that the ratio of the average values of respective breakdown voltages in argon and xenon is fairly constant - it lies between 0.67 and 0.86 for 0.3 bar and between 0.71 and 0.76 for 0.7 bar discharges, across the whole frequency range (60 kHz - 1 MHz). This corresponds to 12.5% of deviation from the average for 0.3 bar and 4.3% for 0.7 bar discharges, across 1.5 orders of magnitude in frequency.

The difference in the duration of the breakdown process in Ar and Xe ranges from very small values for low frequency (60 kHz) to very large ones for the discharges at 800 kHz. At 60 kHz the difference in the duration of the breakdown process between Ar and Xe could not be observed, because the section of the breakdown process detectable with the camera took part in 600 ns or less. Due to the jitter in the breakdown process, we were not able to reproduce the discharges in a way that would allow us to measure smaller differences in timing of the breakdown process. Therefore, we cannot claim to have observed any difference in the length of the breakdown processes at this frequency. However, we were able to observe differences between the breakdown in Ar and Xe at
higher frequencies, the differences being more pronounced when increasing the frequency. At 800 kHz and 4 mm between the electrode tips, the differences in the duration of the breakdown processes are still very small - the breakdown processes in Ar and Xe take respectively 2 to 5 voltage cycles (1 cycle = 1.25 $\mu$s at 800 kHz) for 0.3 bar and $8 \pm 0.5$ and $13 \pm 0.5$ voltage cycles for 0.7 bar. However, in the case of the larger electrode gap of 7 mm, the differences become more significant. At 0.3 bar, we measured the durations of the breakdown processes to be $17 \pm 2.5$ and $97 \pm 5$ voltage cycles for Ar and Xe, respectively. At 0.7 bar, the difference is just as large: $33.5 \pm 5$ compared to $145 \pm 10$ voltage cycles in argon and xenon, respectively.

4.2.2 Driving frequency

Figure 4.5 shows the development of the discharge in argon at 0.3 bar and at 800 kHz under UV irradiation. Each frame was 1 voltage cycle (1.25 $\mu$s) long, and the individual frames were not taken during the same discharge event, due to the limitations of the equipment. We have made enough observations to be sure that the frame sequence we are showing here represents well the breakdown process under said parameters. The lamp itself, with marked electrodes, and the position of the frames with respect to the breakdown moment are shown in figure 4.6.

There are two important things to notice in these two figures. First, it is evident that the part of the discharge development that we were able to observe took about 15 cycles. This means that the total development time is 15 cycles or more. The fact that the discharge develops in more than one AC cycle is an important property of AC discharges and a part of the reason why high-frequency AC discharges can develop at lower voltages than the respective pulsed discharges. This will be further discussed in the Discussion section.

The second important property is that the discharge does not appear to be streamer-like. The discharge is not even directed from one electrode to the other; it initiates at both electrode tips and it diffuses into the electrode gap between the subsequent voltage cycles. Eventually, light is emitted from the whole electrode gap. We cannot speak of a channel that would appear to grow or propagate in a single direction from one electrode tip towards the other. However, one should bear in mind that our camera gate was 1 voltage cycle long during this investigation, which is a time 2 to 3 orders of magnitude larger than what a streamer takes to develop. It is, therefore, possible that there are
Figure 4.5: The development of a UV-aided 800 kHz argon discharge. The pressure was 0.3 bar and the electrode gap was 7 mm long. The gate width of the camera was 1 voltage cycle (1.25 µs). The positions of the individual frames with respect to the breakdown moment is shown in the next figure. The frames were not taken from the same discharge, as the equipment we used did not enable us to do so. For the sake of clarity, the picture of the lamp was added as an additional layer on top of the photographs of the discharge itself. In this way it is clear where exactly in the lamp the breakdown process takes place. The figure is presented in false colour.
Figure 4.6: An enlarged photograph of a lamp is shown on the top, with the active and the grounded electrode clearly marked. Below, we show a schematic representation of the timing of the photographs in the previous figure with respect to the breakdown moment. It can be seen that at 800 kHz the breakdown process in 0.3 bar argon takes around 15 voltage cycles to develop.

streamers forming in the electrode gap and that we used a camera gate too long to see them. On the other hand, one expects an integrated photograph of many streamers that formed in a certain time interval to look much differently [82]. The photographs of the discharge development were taken from the irradiated lamps, with the slowly rising voltage amplitude slope.

Figure 4.7 shows a few frames in the breakdown process in the same gas and pressure, but at 60, 220 and 400 kHz. The photographs taken at the two
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Figure 4.7: The highlights of the discharge formation in argon at 0.3 bar and at electrode gap of 7 mm, in 60, 220 and 400 kHz. The top two rows of photographs show the 60 and 220 kHz breakdown processes, and were taken with the older camera (the Princeton Instruments FMax-512R with a 512 \( \times \) 512 pixel CCD array). The second two photographs of the 60 kHz process were scaled in intensity in a different way than the first two, in order to show more details of the discharge growth. The thin stripe appearing at the top of the lamp burner is a reflection of the UV lamp, it has no connection to the breakdown process. The bottom row shows the 400 kHz breakdown process. For this frequency, the photographs of the discharge process are overlayed with the image of the lamp, in order to have a clear idea about the growth process.
lower frequencies are not of the same high quality as are the photographs taken at higher frequencies, but it is clear that the discharges at lower frequencies are less diffuse and that their growth is directed from one electrode tip to another.

As mentioned earlier, the visible part of the 60 kHz breakdown process took up to 600 ns, so the first row of photographs in figure 4.7 depicts the very last part of the very last voltage cycle before breakdown. In the 220 kHz case, the visible part of the breakdown process took one half of the voltage cycle, and this is shown in figure 4.7. At 400 kHz, the visible breakdown process took about 4 voltage cycles (10 $\mu$s). The photographs in the last row in figure 4.7 show the breakdown process starting from 8.7 $\mu$s before breakdown in the first frame.

The time it takes the discharge to form in the lamp (i.e. the formative lag time) depends on frequency, gas type and pressure. We documented the discharge development time for the part of the process that we could observe. From this set of data we can make a few general conclusions, the first one being that the breakdown process (at least the part that we could observe) becomes longer as the voltage frequency increases. This observation was made from the measurements at the threshold breakdown voltage, which decreases with the increase in frequency. We have already mentioned that in 60 kHz breakdown events, the visible part of the breakdown process was up to 600 ns long, which took only a very small portion of the very last voltage cycle before breakdown. In contrast, at 800 kHz the fastest discharges (Ar and Xe at 0.3 bar and 4 mm electrode gap) take 2 voltage cycles to develop ($2 \times 1.25 \mu$s), and the slowest one (Xe at 0.7 bar and 7 mm EA) takes as much as $145 \pm 10$ voltage cycles ($181.25 \pm 12.5 \mu$s).

We have also learned that the discharges in 0.7 bar always take longer to develop than the discharges in 0.3 bar. The aforementioned data supports this claim, and this result is not surprising; it has been known for a long time that the mean electron energy is lower in higher pressures, due to the higher electron-atom collision frequency. As a consequence, the discharges at high pressures will develop more slowly than the lower pressure discharges at the threshold voltage needed for breakdown.

As a general rule for both gasses, both pressures and both gap lengths, we found that when the frequency was increased, the breakdown voltage decreased. This is shown in figures 4.8, 4.9 and 4.10. The change of breakdown voltage over the frequency range varied between 24.8% and 26.2% for 0.3 bar discharges.
Figure 4.8: The figure shows the breakdown voltages for all argon lamp types over the whole frequency range. The breakdown process was aided by UV irradiation. Increase of the voltage frequency causes lowering of the breakdown voltage.

Figure 4.9: The figure shows the breakdown voltages for all xenon lamp types over the whole frequency range. The breakdown process was aided by UV irradiation. Increase of the voltage frequency causes lowering of the breakdown voltage.
AC breakdown - Experiments

Figure 4.10: Breakdown voltages as a function of frequency for all argon lamp types for unaided breakdown processes. Like in the UV-aided measurements, increase of frequency causes lowering of the breakdown voltage. This effect is present in all lamp types, regardless of the presence of UV irradiation or radioactive materials.

The lowering of the breakdown voltage for 0.7 bar discharges was between 14.7% and 14.8% for Xe, and between 20.1% and 22.3% for Ar.

Since the measurements done without UV irradiation have a large statistical spread (see figure 4.10), the estimations for the change of breakdown voltage over the frequency range were done for the UV-assisted measurements only. The effect of UV irradiation will be shown next and discussed in the following section. It is important to notice that the drop of the breakdown voltage with the increase of frequency is present both in UV-assisted and non-assisted measurements. We have observed the same behaviour for all lamp types.

4.2.3 UV-related effects

The example of the breakdown voltages measured for 0.7 bar Xe shown in figure 4.11 demonstrates the two main consequences of the usage of UV irradiation during the breakdown process. The first effect is a significant lowering of the breakdown voltage, in this case by 43% to 53%. The second effect is a significant decrease in standard deviation in the measured breakdown voltages.
Figure 4.11: The breakdown voltages as a function of frequency for the breakdown process in Xe at 0.7 bar. The effect of the UV irradiation is twofold: it reduces both the breakdown voltage and the standard deviation in the measured values. The size of the electrode gap has virtually no influence in the case of UV-assisted breakdown, most likely because the breakdown process is driven by the high electric field at the electrode tips, not in the lamp centre.

In this figure, the decrease in standard deviation is as big as 80% to 90%. This drastic decrease suggests a lowering of statistical lag of the breakdown process when using UV irradiation. Both effects are present at all frequencies and for all lamp types.

An additional effect can be seen in figures 4.10 and 4.11 for non-aided breakdown, breakdown voltages for 7 mm electrode gap were almost always lower than for 4 mm electrode gap. This is a statistical effect. The lamps we use are very small and the probability of a free electron appearing in the electrode gap by means of cosmic radiation or similar is very low. In addition, this probability is almost twice as small for a 4 mm gap compared to a 7 mm gap. This is the source of the bigger statistical lag in 4 mm electrode gaps.

4.2.4 $^{85}$Kr

‘Ignition helpers’ are popular additions to lamp systems because they ensure lower breakdown voltages and a higher probability of a successful breakdown event. While UV irradiation provides photons that help create free electrons
Figure 4.12: Comparison of the influence of $^{85}$Kr and UV irradiation on the breakdown voltage in Ar at 0.3 bar, at 7 mm electrode gap. Even though $^{85}$Kr is an unstable isotope and works as a direct source of electrons, its influence is not as large as the influence of UV irradiation.

from an electrode by means of the photoelectric effect, radioactive materials can also be chosen to directly produce free electrons, which can, depending on their energy, more or less successfully start electron avalanches. We used a common dosage of 2.5 MBq/L (or 67.5 $\mu$Ci/L) of $^{85}$Kr in Ar to probe the influence of radioactive materials. Figure 4.12 shows the influence of $^{85}$Kr on the breakdown process in 0.3 bar Ar. Under these conditions, we measured breakdown voltages lowered by 16% to 27% with respect to the non-aided case. The most significant lowering of the breakdown voltage with the aid of $^{85}$Kr was measured for the 0.7 bar discharge ($38 \pm 9\%$). The $^{85}$Kr dosage was determined at atmospheric pressure. This means that when filling the lamps with the noble gas, there will be $7/3$ times more $^{85}$Kr in the 0.7 bar lamps than in the 0.3 bar lamps. This is why $^{85}$Kr has a bigger influence on breakdown voltage at the higher pressure.

Even though radioactive materials lower the ignition voltage, they still do not reduce it to the UV-assisted level, as can be seen from the figure. The standard deviations of the breakdown voltage measurements also stay almost as large as for non-assisted measurements, suggesting that the statistical lag of the breakdown process is not significantly decreased.
4.3 Discussion

In this chapter we presented electrical and optical measurements that characterize the breakdown process in argon and xenon under high-frequency driving voltages. We have shown results that call attention to the influence of the driving frequency, the gas type and pressure, and the two ignition helpers - UV irradiation and radioactive material.

4.3.1 Key processes in AC breakdown

In previous work concerning AC breakdown in the frequency ranging from 100 kHz to about 50 MHz [9,26,109–114], there were two ideas about the processes that are important in the discharge development and why AC breakdown is possible at lower voltages than is the case for the pulsed breakdown. The first explanation concerns the limited drift of electrons within the electrode gap between the electrodes at high enough frequencies, limiting drift losses and effectively increasing the ratio of electron source and sink in a single voltage cycle. In the case when frequency is not high enough, the second proposed solution is the accumulation of the heavy charges in the electrode gap, eventually creating local density high enough to modify the externally applied electric field and basically start a streamer-like process. First we will deal with the first proposition.

Figure 4.13 shows the electron drift distance over one half of a 1 MHz voltage cycle for argon and xenon, as a function of reduced electric field. The drift distance \( x \) was calculated using a standard relation for the drift distance in an AC field, taking into account the sine shape of the electric field.

\[
x = \frac{-qE_0}{m\omega\sqrt{\omega^2 + \nu_{col}^2}} \sin(\omega t)
\]  

(4.1)

\( q \) is the electron charge, \( m \) the electron mass, \( E_0 \) is the amplitude of the electric field, \( \omega \) the angular frequency the oscillating electric field and \( \nu_{col} \) is the electron-atom collision frequency for momentum transfer. In our case, \( \nu_{col} \gg \omega \), which means that we can write the afore mentioned expression as

\[
x = \frac{-qE_0}{m\omega\nu_{col}} \sin(\omega t) = \frac{-q(E_0/N)}{m\omega(\nu_{col}/N)} \sin(\omega t)
\]  

(4.2)
Figure 4.13: The drift distance of electrons in 1/2 of a 1 MHz voltage cycle in Ar and Xe in the reduced electric field range used in our experiments. The two horizontal lines represent the electrode gaps in the geometries we employed.

Figure 4.14: The drift distance of electrons in 1/2 of a 0.4, 0.6, 0.8 and 1 MHz voltage cycle in Xe in the reduced electric field range in our experiments.
The amplitude of the electric field strength can be estimated by simply dividing the voltage across the electrodes by the length of the electrode gap $E_0 = V_0/L$, which holds approximately only in the center of the lamp. The $E_0/N$ range evaluated in this way is 20 - 80 Td in the center of the lamp. One should keep in mind that the $E_0/N$ values at the electrode tips are much larger than in the lamp center, which leads to underestimation of the drift distances. In a symmetrical system such as ours, the amplitude of the electric field strength can be estimated as $E_0 = V_0/(2R)$, where $R$ is the radius of curvature of the electrode tip. Therefore, the average reduced electric field strength in the lamp is underestimated by factor $L/4R$, and by factor $L/2R$ at the electrode tips. Taking $R$ to be equal to the electrode radius $R = 0.3$ mm, the factor $L/4R$ equals 3.3 and 5.8 for 4 mm and 7 mm electrode gap, respectively. The two horizontal lines in figure 4.13 represent the two electrode gaps used in the experiments - 4 and 7 mm.

It can be seen that the frequency range we used does not provide fast enough oscillations for our small electrode gaps (4 or 7 mm) to limit the electron drift losses, at least not for argon discharges. The electrons in xenon appear to have a drift distance that is comparable to the gap length at low $E_0/N$ values, but as we mentioned already, the drift distances are underestimated. We cannot claim to have a transition to the breakdown mode where the electron drift losses are lowered by a significant amount. At higher frequencies we expect there to be a transition to this mode of operation, with further lowering of the breakdown voltage.

Regarding the second proposition offered when explaining a lower breakdown voltage in the case of AC voltage signal [9], in chapter 5 we will show by means of modelling that the local densities of accumulated heavy charge are not high enough during the time before the breakdown to modify the electric field imposed by the rod-shaped electrodes that we used in the experiments.

The aforementioned theories have a greater influence in other combinations of gas, pressure, voltage frequency and electrode gap than in our case. However, there are a few additional important aspects in AC breakdown process that distinguish them from pulsed breakdown. The first one is that the discharge in high frequencies develops over several voltage cycles, as we have shown in figures 4.5, 4.6 and 4.7. This fact suggests that the time allowed to the AC discharge to develop (10 to 50 ms in our case) is several orders of magnitude larger than the typical times associated with pulsed breakdown, in 10-100 ns order of magnitude. One typical result for pulsed breakdown is that the
breakdown voltage decreases as the voltage ramp decreases, as has been shown in chapter 2 as well as \([116]\). This suggests a significant overvoltage during the pulsed breakdown process. The overvoltage occurs simply because the voltage rises too quickly (the pulses used are very narrow), and at typical discharge growth speeds of \(10^5\) to \(10^6\) m/s (\(82\), chapter 2), the discharge grows too slowly to fully form before a significant overvoltage occurs. In the case of AC breakdown, there is no significant overvoltage caused by the formation time because of the very slow ramp of the voltage amplitude.

There is another aspect of the AC ignition process that makes it very different from pulsed breakdown. The fact that the discharge develops in several cycles, while we still have large electron losses due to drift, suggests the relative importance of the heavy particles whose density does not strictly follow the AC signal. Here we are talking about atom metastables and molecular ions, that also form in relatively high densities, due to the high pressure (0.3 and 0.7 bar) we were working in. Unlike electrons, these particles do not drift and diffuse far away from the electrode tips (the places of highest particle production) during a single voltage cycle. Metastables are electrically neutral, so they just diffuse away from the place they were produced at, but molecular ions are charged and they drift back and forth from electrode tips, thus making secondary electron emission from electrode surface one very important aspect in which AC breakdown differs significantly from the pulsed ignition process. We suggest that this is one of the key reasons why the AC process occurs at much (up to 50% \([9,26]\)) lower voltage for breakdown. The details are presented in chapter 5.

4.3.2 Breakdown process in argon and xenon

Both argon and xenon are noble gasses, which makes the chemistry during the breakdown process fairly simple, assuming pure gas environment - we have direct and stepwise ionization by electron collision, associative collisional ionization of metastables and three-body associative collisional process between atomic ion and neutral gas atoms. The reverse processes are also present, the most important being associative recombination and collisional deexcitation of metastables (see table 4.2). The reactions given in table 4.2 represent a simple model including processes with the most influence on the breakdown process in pure Ar of Xe. Additional reactions are also possible \([95,117]\). The important thing to notice is that there are two classes of reactions mentioned - the first
one depending on the electron energy and density, and the second one depend-
ing only on the density of the heavy particles. It is also important to realize
that the heavy particles which take part in the second class of reactions are
created in the reactions belonging to the first reaction class. It is a kind of a
chain process, the beginning of which heavily depends on electron properties.

**Table 4.2:** Reactions in an AC breakdown process. In this case, X stands for
Ar or Xe.

\[
\begin{align*}
  e + X & \rightarrow e + X^* \\
  e + X^* & \rightarrow e + e + X^+ \\
  e + X & \rightarrow e + e + X^+ \\
  X^+ + X + X & \rightarrow X_2^+ + X \\
  X^* + X^* & \rightarrow X^+ + X + e \\
  X^* + X^* & \rightarrow X_2^+ + e \\
  X^* + e & \rightarrow X + e \\
  X^+ + e + e & \rightarrow X + e \\
  X^+ + e & \rightarrow X + h\nu \\
  X_2^+ + X & \rightarrow X^+ + X + X \\
  X_2^+ + e & \rightarrow X^* + X
\end{align*}
\]

When we compare basic properties of argon and xenon as presented in ta-
ble [4.3] we see that argon has a higher ionization potential and higher-lying
metastable states, which makes it more difficult to ionize than xenon. There-
fore, for the same conditions, an argon discharge should have a higher threshold
voltage needed for breakdown than a xenon discharge. However, this is not the
case, as we have shown in almost every figure in this chapter. The explanation
for this effect is of a fundamental nature, and does not bring new knowledge.
However, it will also help us to explain other differences between argon and
xenon.

It is true that for equal electron energies, xenon is easier to ionize than argon,
but for the same reduced electric field, mean electron energies in argon and
xenon are different. One basic property of an atom is its size, and we know that
the xenon atom (radius 108 pm) is much larger than the argon atom (radius
71 pm), because it has two extra filled electron shells. As a consequence, the
electron-atom elastic collision frequency is almost twice as large in xenon than
Table 4.3: Basic properties of argon and xenon.

<table>
<thead>
<tr>
<th>property</th>
<th>argon</th>
<th>xenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>atomic weight</td>
<td>40</td>
<td>131.3</td>
</tr>
<tr>
<td>radius</td>
<td>71 pm</td>
<td>108 pm</td>
</tr>
<tr>
<td>ionization level</td>
<td>15.76 eV</td>
<td>12.13 eV</td>
</tr>
<tr>
<td>lowest lying</td>
<td>11.55 eV</td>
<td>8.32 eV</td>
</tr>
<tr>
<td>metastable level</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

in argon in our experimental conditions [7]. The electron-atom elastic collisions are important because they influence the electron energy and electron velocity distribution, which causes large differences during the breakdown process, the differences that cannot be explained by mere comparison of the ionization potentials.

Mean electron energies for the reduced electric field we had in our experiments are shown in figure 4.15. One can see that the mean electron energy of xenon is significantly lower than that of argon, for the same \( E_0/N \) values; this is why xenon is harder to ionize at the same externally applied voltage.

The \( E_0/N \) range we show in the graph is quite large, and in fact wider than that which we expect in the experiment. However, one should not lose sight of the non-uniformity of the electric field in a pin-to-pin electrode geometry. The electric field governing the processes is the one at the electrode tip, not the one that can be easily estimated for the center of the electrode gap. Even though we used simple rod-shaped electrodes without sharp tips, we still expect the electric field to be significantly larger at the electrode tips than anywhere else in the lamp.

Since the electron energy is more efficiently lost in xenon, this could be a possible explanation as to why the discharge formation in xenon takes so much longer than in argon. We know that the mean electron energy depends on the electron-atom collision frequency - the higher the frequency, the lower the mean electron energy. There are two ways for increasing the collision frequency, one of which is increasing the gas pressure, and the other to increase the atom size, because the elastic electron-atom collision frequency depends on the polarizability of the atom, and for noble gasses this value scales with the volume of the atom. This suggests that the increase of atomic size has a similar effect.
as the increase of the pressure of the neutral gas. This is also something we have observed and described in the Results section - the 0.7 bar discharges take longer time to develop than 0.3 bar discharges, similar to the way the xenon discharges take a longer time to develop than argon discharges. The reason behind both these effects could be that a lower mean electron energy means that more time is needed to build a charged channel between the electrodes.

Building on this explanation, it becomes clear why discharges in lighter noble gasses are as a rule easier to ignite than the ones in the heavier gasses. Also, introducing very small fractions of heavier noble gas in a lighter noble gas atmosphere results in even easier breakdown that requires even lower voltages. This is because the mean electron energy is determined by the atmosphere of the lighter noble gas, while the small fraction of the heavier noble gas is used for ionization purposes, due to its lower ionization potential. This has been shown numerically [95].

However, this is not the whole difference between the two gas types. One should not forget the differences in ionization potentials, metastable levels and reaction coefficients for the processes we have identified as important. Simulations taking all these phenomena into account are required to understand their...
4.3.3 Influence of voltage frequency

In the Results section, we have shown in many figures that one effect is always present - the lowering of the breakdown voltage with the increase of frequency. This is a result which is also in agreement with the data published by Beckers et al. [26]. As we have shown already, this effect cannot be explained by the lowering of electron drift losses or by accumulation of heavy charge that modifies the local electric field. However, the explanation does lie in the heavy species present in the discharge. The explanation we are proposing is described in more detail in chapter 5 as it is a result of simulations. Here we offer only a short explanation.

The process which we believe is responsible for the decrease of the threshold voltage needed for breakdown when the frequency is increased is secondary electron emission from the electrode surface. There is only one important heavy species, the molecular ions. The reason why the atomic ions do not play a significant role is that their density is very low, due to very efficient three-body associative collisional process with neutral atoms, in which molecular ions are created. The reason why the metastable species are not as important as the molecular ions is that they are not charged, so they don’t drift back and forth around the electrode tip - they just diffuse away.

The molecular ions are created at the electrode tip around the time when the voltage is at its extreme. They then drift away until the polarity changes, at which point they start drifting back towards the electrode. When they reach the electrode, the secondary electron emission occurs with a certain probability.

While the molecular ions drift back and forth, their density decreases due to diffusion and recombination processes, and they return to the electrode surface in smaller numbers. If the frequency is increased, the fraction of the molecular ions that return to create secondary electrons is also increased. More secondary electrons means better effective ratio between the source and the sink of electrons during a single voltage cycle, which eases the breakdown process and allows it to take place at a lower voltage. A more detailed set of results can be found in chapter 5.
4.3.4 UV-related effects

When estimating the effects of the voltage frequency on the breakdown process, we have used breakdown voltage measurements for UV-assisted breakdown events, because UV-assisted processes gave rise to much smaller deviation from the mean value. In this way we were able to draw conclusions that cannot be dismissed due to large error bars of the non-assisted breakdown processes. We have also shown in several figures that the behaviour of the UV-assisted and non-UV-assisted measurements is the same over the whole frequency range, but to really claim that the same conclusions hold for both UV-assisted and non-assisted breakdown processes, we have to consider the impact of the UV irradiation.

One aspect is certainly photoemission of electrons from the surfaces within the lamp. The 254 nm (4.9 eV) UV photon generated by the UV source used in the experiments can produce a photoelectron by means of the photoelectric effect from the surface of the electrode made of tungsten (W ≈ 4.5 eV). As such, the UV irradiation works as an effective electron source near the electrode surface, thus supplying the gas volume with enough free electrons to minimize the statistical lag otherwise induced by the lack of initial free electrons [90]. This effect can indeed have a big influence on the availability of the free electrons in the gas at all times, as the UV source we used had the output flux high enough to flood the lamp volume with $10^{13} - 10^{14}$ 254 nm photons per second. The quantum yield for electron emission from near-visible UV has been estimated to about $10^{-3}$ [7].

We do not expect the photoemission of electrons from the burner wall to play a significant role, because the burner is made of YAG, which is a dielectric material. Consequently, there is no charge redistribution in the material that can follow massive electron emissions. This is why the dielectric surface was not considered as a major electron source under the influence of UV irradiation.

UV irradiation also works as an effective dielectric surface cleaner - if the surface was left charged by electrons in the previous breakdown process, the UV photons have enough energy to detach the charge from the surface [119]. If there were surface discharges forming on the dielectric surface of the lamp burner during the breakdown processes in our experiments, this would mean that the UV irradiation would cause a fundamental deviation from the non-UV-irradiated case. However, our discharges form in the gas volume between the electrodes and do not grow on the surrounding dielectric surfaces.
Another way in which the UV irradiation can possibly influence the breakdown process is the effects it has on the chemistry of the breakdown process. Namely, a 4.9 eV photon has enough energy to ionize an argon or a xenon metastable. The energies needed are 4.2 and 3.2 eV respectively. In this respect, the collisional ionization process by electron impact of the atomic metastables is at least partly replaced by a photoionization process. However, we do not believe that this has a major effect on the breakdown process in either gas. Even if the cross sections for this kind of photoionization were very large, the metastable density in the near-atmospheric pressure gas that is undergoing the transition to become a plasma is not significant enough for this process to create a noteworthy shortcut between the metastable and atomic ion state. In any case, the result would most likely be a modest shortening of the breakdown process, we do not expect the threshold voltage needed for breakdown to be affected.

The formative time could, therefore, be slightly shortened as a consequence of easier ionization of atomic metastables. However, we must consider the opposite effect as well. It has been shown for pulsed discharges that the overvoltage has a great influence on formative time, namely that the formation time grows as the overvoltage is decreased [120][121]. This effect is caused by the specific link between the Townsend’s first ionization coefficient and the reduced electric field $\alpha/p = A \exp(-Bp/E)$ [7], where $A$ and $B$ are gas-specific coefficients. The multiplication of electrons in an avalanche exponentially rises with $\alpha$, which is itself a steep function of the reduced electric field [7]. Consequently, already a small increase of voltage above the threshold level leads to large reduction of the formative lag time. During the UV-assisted measurements the overvoltage is very small, if present at all. Therefore, the formative time of the UV-assisted breakdown is much larger than that of the non-assisted process. There are, thus, two effects modifying the formative time of breakdown in our experiments, one reducing it and one magnifying it. If a parallel can be drawn with the work of Moss et al in lower pressures [121], the balance is on the side of formative lag time magnification.

In conclusion, we believe that the only significant influence of the UV irradiation in our experiments is the creation of the free electrons needed to start an electron avalanche, thus effectively reducing the statistical lag to a minimum. The increase of the formative lag is negligible when considering both effects on the same time scale.
4.3.5 Role of $^{85}$Kr

The presence of $^{85}$Kr in our experiments was shown to cause some lowering of the breakdown voltage and no change in the standard deviation from the mean of the measured values, which would suggest that there is no significant reduction of the statistical lag. As a direct source of electrons, at a first glance, it was supposed to provide the gas volume with enough free electrons to start an electron avalanche and reduce the statistical lag.

Here we would like to direct the reader’s attention to the very small volume of the lamps in question, i.e. $3.6 \times 10^{-7}$ m$^3$. The low level of radioactivity we used produces only about 900 high-energy electrons per second in the entire lamp, at 1 bar. Scaled down to 0.7 or 0.3 bar, we get 630 and 270 high-energy electrons emitted in the lamp volume per second, respectively. Given that each of our breakdown experiments takes roughly between 10 and 50 ms for the voltage slope of 100 V/ms, we can expect 6 to 31 high-energy electrons per experiment in 0.7 bar lamps and 3 to 13 electrons in 0.3 bar Ar atmosphere. The fact that there are so few electron emission events per experiment can explain the big statistical spread in the measurements, when compared to the UV-assisted measurements, in which about $10^7$ more electrons are generated per second.

Such a small number of emitted electrons per breakdown process gives rise to large statistical lag time. However, every one of these electrons is capable of starting an electron avalanche in the lamp. As the maximum high-energy emitted electron energy is 687 keV, while the mean value is 251 keV, there is a high probability that in the case of a collision with an atom in the gas, or with the burner wall or the electrode surface, this electron will start an electron avalanche. We have calculated that the average distance the 0.2 MeV electrons can travel in 0.3 and 0.7 bar argon before the first collision with a gas atom is 1 mm and 0.45 mm respectively. Therefore, the high-energy electrons are likely to hit any of the three possible targets (an atom, the electrode or the dielectric surface) and start an electron avalanche.

The possible benefits from the usage of radioactive materials such as $^{85}$Kr are evident. Even the low dosage we used in our experiments, and which is the typical dosage used in HID lamps, proved to be enough to make a difference in HID-sized lamps. However, a higher dosage or a longer time available for breakdown are expected to give better results because they should effectively provide the same - more free electrons during the breakdown process.
4.4 Conclusions

An experimental investigation of the AC breakdown process was performed in argon and xenon. We have demonstrated that the discharges are more easily formed in argon than in xenon and offered an explanation based on the differences in electron-atom collision frequencies. The existing explanations as to why the AC breakdown occurs at lower voltages than the matching pulsed breakdown process were reviewed, and some of our own were offered. The changes in electron loss due to drift were found not to have a large role in the lowering of the breakdown voltage as the frequency was increased; secondary electron emission from the electrode surface had a more important impact. More precisely, molecular ions were suggested as the heavy species to control the secondary electron emission from electrode surface by ion impact.
5

AC breakdown in near-atmospheric pressure noble gasses: II. Simulations

Abstract. The effect of frequency on characteristics of AC-driven breakdown processes in 0.7 bar argon is investigated by means of a two-dimensional fluid model. The geometry represents an HID lamp burner with a pin-pin electrode system forming a 7 mm electrode gap. Breakdown process is considered in the frequency range between 60 kHz and 1 MHz. The appearance of the discharge and the influence of the voltage frequency on its characteristics obtained in the simulations are in good agreement with the experimental data presented in the previous chapter. The role of secondary electron emission from the electrode surfaces is demonstrated and linked to the lowering of the threshold voltage with the increase of frequency observed both in experiment and model.

A slightly altered form of this chapter has been accepted for publication in Journal of Physics D: Applied Physics – special issue on LS12/WLED3 symposium.
5.1 System under consideration

![Schematic representation of geometry used in the simulations. The geometry consists of the 400 x 95 square cells. It is cylindrically symmetric, with a symmetry axis at the lower horizontal edge shown in the figure. The left electrode was always active, and the right one grounded. See the text for further details.](image)

**Figure 5.1:** A schematic representation of geometry used in the simulations. The geometry consists of the $400 \times 95$ square cells. It is cylindrically symmetric, with a symmetry axis at the lower horizontal edge shown in the figure. The left electrode was always active, and the right one grounded. See the text for further details.

Simulations presented in this chapter were done in pure argon at 0.7 bar. Given the high pressure, the low ionization degree and the enclosed geometry, it is appropriate to consider the temperature, the pressure and the density of ground state argon as constant in the model. In the simulations, we have observed the evolution of the electrons, atomic metastables representing the two metastable ($4s$) states (Ar*), atomic (Ar+) and molecular (Ar$_2^+$) ions.

Initial densities represent a state of low ionization degree - a typical starting condition in cold HID lamps. Initial densities of electrons and atomic ions were $10^9$ m$^{-3}$, while densities of metastables and molecular ions were zero. An important parameter in these simulations was the secondary electron emission coefficient from the electrode surface, which was defined separately for every species. The secondary electron emission coefficients are not well known in general, and there is a big spread of values suggested in the literature [7, 15, 100, 122]. We set these parameters to 0.07 for atomic ions and metastables and to 0.04 for the molecular ions. We chose the value 0.07 because it was chosen previously for breakdown simulations in similar conditions [123]. The secondary electron emission coefficient for molecular argon ions was estimated to 0.04 based on [15]: the data suggests that the increase in mass of noble gas
ions while keeping charge constant decreases the secondary electron emission coefficient in the assumed ratio. For reference, we compared the secondary electron emission coefficients of Ar$^+$ and Kr$^+$, two ions with mass ratios of approximately 2.

Table 5.1 lists the reactions used in the simulations. In comparison with fast development of the discharge in pulsed voltage mode, as described in chapter 3, development of the discharges described here is much slower (up to 100 µs compared to 150 ns in the pulsed mode). As a consequence of this prolonged simulation period, these simulations require a broader reaction list that includes the recombination processes as well, as given in table 5.1. For a better overview of the included processes, the reaction list is divided into two parts. The first part features excitation and ionization processes, most efficient being processes number 1 and 3, excitation and direct ionization of argon atoms by electron impact. Reaction 4, the collisional process in which molecular ions are created, is very important in near-atmospheric pressure chemistry because it involves a collision of an atomic ion with two ground state atoms, depleting the atomic ion supply. Reactions involving atomic metastables may not play the main role in the breakdown chemistry, but we have already shown that even for fast breakdown processes, they do give a contribution that cannot be neglected, as shown in chapter 3. The rest of the process list consists

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
No. & Reaction & Reaction coefficients $k_r$ & Ref. \\
\hline
1 & $e + Ar \rightarrow e + Ar^*$ & $f(\varepsilon)$ & 99 \\
2 & $e + Ar^* \rightarrow 2e + Ar^+$ & $f(\varepsilon)$ & 99 \\
3 & $e + Ar \rightarrow 2e + Ar^+$ & $f(\varepsilon)$ & 99 \\
4 & $Ar^+ + 2Ar \rightarrow Ar_2^+ + Ar$ & $2.5 \times 10^{-43} \text{m}^6 \text{s}^{-1}$ & 101 \\
5 & $2Ar^* \rightarrow Ar^+ + Ar + e$ & $1.2 \times 10^{-15} \text{m}^3 \text{s}^{-1}$ & 101 \\
6 & $2Ar^* \rightarrow Ar_2^+ + e$ & $2.03 \times 10^{-15} \text{m}^3 \text{s}^{-1}$ & 124 \\
7 & $e + Ar^* \rightarrow e + Ar$ & $f(\varepsilon)$ & 99 \\
8 & $2e + Ar^+ \rightarrow e + Ar$ & $5.4 \times 10^{-39} \times T_e^{-9/2} \text{m}^6 \text{s}^{-1}$ & 102 \\
9 & $e + Ar^+ \rightarrow Ar + h\nu$ & $1 \times 10^{-17} \text{m}^3 \text{s}^{-1}$ & 102 \\
10 & $Ar_2^+ + Ar \rightarrow Ar^+ + 2Ar$ & $2.496 \times 10^{-36} \text{m}^3 \text{s}^{-1}$ & 103 \\
11 & $e + Ar_2^+ \rightarrow Ar^* + Ar$ & $7 \times 10^{-13} (300K/T_e)^{1/2} \text{m}^3 \text{s}^{-1}$ & 101 \\
\hline
\end{tabular}
\caption{Reaction coefficients used in the simulations.}
\end{table}
of four recombination and one deexcitation process. The rates for excitation, deexcitation and ionization of argon atoms were obtained using the Boltzmann solver BOLSIG+ \cite{99}.

The geometry used in the simulations is shown in figure \ref{fig:5.1}. It represents the real system used in the experiments performed on AC breakdown and described in chapter \ref{chap:4}. The geometry represents a 70 W HID Philips burner made of YAG (Yttrium Aluminium Garnet) with relative permittivity $\epsilon_r = 11.7$, tungsten electrodes and the plasma region. Thickness of the burner wall is 0.6 mm, and electrode radius is 0.3 mm. The background gas in the plasma region is argon at 300 K and 0.7 bar. The geometry of the burner in the model was constructed to resemble the experimental one as much as possible, regardless of the fact that a rectangular grid we used did not always allow for smooth surfaces. Imposing different geometry features that are not present in reality, such as $90^\circ$ corners in the dielectric burner, creates regions of unrealistically high electric fields at such places. We have therefore avoided approximating a sphere-like burner used in the experiments with a cylinder.

The electrodes used in the experiment were rod-shaped with a diameter of 0.3 mm. In the model, we have made a slight adaptation, also shown in figure \ref{fig:5.1}. The adaptation was made because in simulations using simple rod-shaped electrodes gave the highest electric field at the edges of the electrodes. As a consequence, a discharge would start forming at the edge to create a tunnel-shaped formation that would propagate through the gas volume. This never occurs in experiments because the electrode system is never perfectly symmetric, like in a 2D cylindrically-symmetric geometry of our fluid model. In addition, microstructures on the electrode surface create points of high local electric field. These two effects combined make it highly unlikely for the real discharge to incept and propagate in the same way it does in the model with simple rod-shaped electrodes. To circumvent this problem, we introduced one extra cell in each electrode, in the middle of the electrode cross section, at the symmetry axis; we also took away one cell at the $90^\circ$ edge of the electrode, to lower the local electric field at that point. As a result, the discharge always initiates at the symmetry axis, making our model more similar to what happens in reality (chapter \ref{chap:4}). We would like to stress that the changes we have made to the electrode geometry do not in any way challenge the validity of our results. We simply moved the spot of highest electric field from one place to another, otherwise keeping the electrode geometry unchanged.

There are two electrodes in the modelled system - one active and one
AC breakdown - Simulations

grounded, like shown in figure 5.1. The potential of the grounded electrode is kept at zero during the simulations, while a sinusoidal signal of amplitude $A$ and frequency $\nu$ is applied to the active electrode,

$$V_{ActEl} = A \sin(2\pi \nu t).$$

The simulations were done for four frequencies in the frequency range used in the experiments described in chapter 4: $\nu = 60 \text{ kHz}$, $100 \text{ kHz}$, $400 \text{ kHz}$ and $1 \text{ MHz}$.

The grid used in the computational domain consists of rectangular elements of size $(0.05 \times 0.05) \text{ mm}^2$. The present model does not yet support local grid refinement; this requires a compromise in the chosen size of the grid cells, to accommodate for both the need for small cell size in the entire lamp volume and the prolonged calculation time in a breakdown process that can take up to $100 \mu s$. Given the fact that our discharge does not appear filamentary in experiments and that its minimum thickness can be compared to the thickness of the electrodes, cell dimension of 0.05 mm were found to be sufficiently small for the needs of this particular set of simulations.

5.2 Model

The set of simulations presented in this chapter characterizes the transition from the gaseous to the plasma state in 0.7 bar argon. Thermal equilibrium is not reached during the related experiments (chapter 4) nor is it assumed in the calculations. While the electron energy can reach above 10 eV, the energies of the ions in the process remain low.

The model used for simulations is a 2D fluid model using a cylindrically-symmetric geometry. It is a part of the modelling toolkit PLASIMO [104] developed in Eindhoven University of Technology. The model was originally created and documented by Hagelaar and Kroesen [105,106] for plasmas in display devices. It has been further developed for many other applications [104]. As far as lighting purposes are concerned, the extensions done for modelling ignition in fluorescent tubes [91,92] were done by van Dijk and Brok. It was later used for simulations of a breakdown process with fast-rising voltage in near-atmospheric pressure gas (chapter 3). For the present set of simulations, we took into account the transport of all heavy species except the neutral gas.
Table 5.2: Transport coefficients used in the simulations. $\mu_p$ is the particle mobility, and $D_p$ represents the diffusion coefficient.

<table>
<thead>
<tr>
<th>Species</th>
<th>$\mu_p$</th>
<th>$D_p$ [Torr cm$^2$ s$^{-1}$]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>$f(\epsilon)$</td>
<td>Einstein relation</td>
<td>99</td>
</tr>
<tr>
<td>Ar*</td>
<td>–</td>
<td>82.992</td>
<td>100</td>
</tr>
<tr>
<td>Ar$^+$</td>
<td>$f(E/N)$</td>
<td>Einstein relation</td>
<td>99</td>
</tr>
<tr>
<td>Ar$_2^+$</td>
<td>$f(E/N)$</td>
<td>Einstein relation</td>
<td>99</td>
</tr>
</tbody>
</table>

atoms. Secondary electron emission from the electrode surfaces was also taken into account.

The two-dimensional fluid model uses the control volume method for solving equations for the electrostatic potential and particle and electron energy density. The grid we used is composed of rectangular elements $\Delta x$ and $\Delta y$ in size that represent the plasma region, an electrode or a dielectric material. The Poisson equation is solved in the plasma region and in the dielectric materials; the transport equations are solved only in the plasma region.

5.2.1 Fluid model

As mentioned, the model we used for the simulations presented in this chapter was already used and described in chapter 3 in a somewhat simpler form for pulsed discharges in 0.7 bar argon in a pin-pin geometry. We will shortly restate the main principles in the following section.

A fluid model solves balance equations for particles and energy in order to describe a physical system. The general form of the balance equation for particle species $p$ with density $n_p$, flux density $\Gamma_p$ and source term $S_p$ is as follows

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \Gamma_p = S_p$$

(5.2)

The density, flux density and the net source term are functions of space and time. The net source term consists of contributions from the reactions that create or destroy the particles of the given type $p$. The source or the sink term is given as a product of the net stoichiometric factor $c_{r,p}$ and the reaction rate $R_r$ for a given reaction of type $r$. The net source term $S_p$ for species $p$ is given
as the sum over all the relevant reactions.

\[ S_p = \sum_r c_{r,p} R_r \]  

(5.3)

The flux density \( \Gamma_p \) is approximated by the drift-diffusion equation:

\[ \Gamma_p = \mu_p E n_p - D_p \nabla n_p \]  

(5.4)

The first term on the right-hand side represents the drift, it is characterized by the particle mobility \( \mu_p \) and proportional to the imposed electric field in the system \( E \). Mobility can be positive, negative or zero for species that are not charged. The second term refers to the diffusive flux, proportional to the gradient of the particle density and the diffusion coefficient \( D_p \).

Diffusion coefficients for the charged species are calculated from the Einstein relation (table 5.2).

\[ D_p = \frac{k_B T_p \mu_p}{q_p} \]  

(5.5)

There are two important values needed for the calculation of the diffusion coefficients - particle mobility, and ion temperature. Particle mobilities \( \mu_p \) are given as a simulation input parameter in a table, and the ion temperatures are calculated by the model. The ion temperatures are taken as the surrounding gas temperature, corrected for the heating caused by the electric field \[107\]

\[ k_B T_i = k_B T_g + \frac{m_i + m_g}{5m_i + 3m_g} m_g (\mu_i E)^2 \]  

(5.6)

\( T_i \) is the ion temperature, \( T_g \) is the temperature of the surrounding buffer gas and \( m_i \) and \( m_g \) are the corresponding masses.

Because of the small electron mass which causes poor energy transfer in electron-neutral collisions, equation 5.6 does not hold for electrons. Instead, the local mean electron energy is given by the energy balance equation

\[ \frac{\partial (n_e \varepsilon_e)}{\partial t} + \nabla \cdot \Gamma_\varepsilon = -e \Gamma_e \cdot E + S_\varepsilon \]  

(5.7)

Electron energy density is given as a product of the electron density and the mean electron energy \( n_\varepsilon = \varepsilon n_e \).

The first term on the right-hand side of equation 5.7 stands for the heating (energy gain) from the electric field. The second term \( S_\varepsilon \) is an analog of the
net source term for the particle density. The electron energy $\varepsilon_r$ can be gained or lost in reactions with the associated reaction rate $R_r$.

$$S_\varepsilon = - \sum_r c_r \varepsilon_r R_r \quad (5.8)$$

Mean energy flux density $\Gamma_\varepsilon$ can be expressed as

$$\Gamma_\varepsilon = \frac{5}{3} \mu_e E n_\varepsilon - \frac{5}{3} D_e \nabla n_\varepsilon \quad (5.9)$$

The second term in the equation above is the heat conduction flux, proportional to the gradient of the mean electron energy.

Local electron temperature necessary for the calculation of the electron diffusion coefficient can be calculated from the local mean electron energy as $k_B T_e = (2/3)\overline{\varepsilon}$.

Electric field in the system is calculated by solving the Poisson equation.

$$\nabla \cdot \epsilon \nabla \varphi = -\nabla \cdot \epsilon E = -\sum_p q_p n_p \quad (5.10)$$

### 5.2.2 Treatment of charge at the interfaces of two media

Boundary conditions used in this model were described in detail in [105]. Here we will describe them in short.

Poisson equation is solved in different regions in the computational domain, such as the discharge region and the dielectric region, with a given permittivity $\epsilon$. The electrode potentials are boundary conditions for the plasma-electrode boundary. Homogenous Neumann boundary conditions are used for potential, particle densities and electron energy density at open boundaries.

The boundary condition for the Poisson equation at the dielectric-plasma interface (*the interface* in the remainder of the section) is determined by the surface charge density $\sigma$ at the interface. The effect is given by Gauss’s law

$$\sigma = \epsilon_{\text{dielectric}} E_{\text{dielectric}} \cdot e_\perp - \epsilon_0 E_{\text{plasma}} \cdot e_\perp \quad (5.11)$$

where the electric fields are given at the interface. $e_\perp$ is the normal vector pointing towards the interface.
Surface charge density is included in the Poisson equation in an additional term on the right-hand side of equation (5.10). Surface charge density $\sigma$ resulting from the charged particles hitting the wall at the moment $t$ has the following form [106]:

$$\sigma = \int_0^t \left[ \sum_p q_p (\mathbf{\Gamma}_p \cdot \mathbf{e}_\perp) \right] dt'$$  \hspace{1cm} (5.12)\text{\textdagger}

The flux of charged particles directed to the surface is given by [105]

$$\mathbf{\Gamma}_p \cdot \mathbf{e}_\perp = a_p \mu_p (\mathbf{E} \cdot \mathbf{e}_\perp) n_p + \frac{1}{4} v_{th,p} n_p - \frac{1}{2} D_p (\nabla n_p \cdot \mathbf{e}_\perp)$$  \hspace{1cm} (5.13)\text{\textdagger}

The parameter $a_p$ is equal to one if the drift velocity of the charged particles of type $p$ is directed towards the interface, zero otherwise. The thermal velocity is determined by the particle temperature $T_p$

$$v_{th,p} = \sqrt{\frac{8k_B T_p}{\pi m_p}}$$  \hspace{1cm} (5.14)\text{\textdagger}

The temperature $T_p$ is given by equation (5.6) for heavy charged particles and by the average energy value for electrons. Setting equation (5.13) as the boundary condition for the drift-diffusion equation (5.4), we get the expression that must be satisfied at the interface

$$\mu_p (\mathbf{E} \cdot \mathbf{e}_\perp) n_p - D_p (\nabla n_p \cdot \mathbf{e}_\perp) = a_p \mu_p (\mathbf{E} \cdot \mathbf{e}_\perp) n_p + \frac{1}{4} v_{th,p} n_p - \frac{1}{2} D_p (\nabla n_p \cdot \mathbf{e}_\perp)$$  \hspace{1cm} (5.15)\text{\textdagger}

The left-hand side of the equation gives the continuum expression for the flux valid in the plasma volume, the right-hand side represents the analytical term for the particle flux toward the interface due to the drift motion in the electric field and the thermal motion of the particles. Ultimately, the expression for the heavy particle flux towards the interface is obtained using equation (5.15) to eliminate the diffusion term from equation (5.13), giving

$$\mathbf{\Gamma}_p \cdot \mathbf{e}_\perp = (2a_p - 1) \mu_p (\mathbf{E} \cdot \mathbf{e}_\perp) n_p + \frac{1}{2} v_{th,p} n_p$$  \hspace{1cm} (5.16)\text{\textdagger}

Because of secondary electron emission, electrons require a more detailed treatment. We cannot simply use the total electron density $n_e$ in the equation (5.16), because it consists of two groups of electrons: electrons coming from the bulk
of the plasma ($\alpha$ electrons) and the $\gamma$ electrons due to secondary emission, $n_e = n_{\alpha} + n_{\gamma}$. Equation (5.16) can be rewritten for $\alpha$ electrons as \[105\]

$$\Gamma_{\alpha} \cdot e_{\perp} = (2a_e - 1)\mu_e (E \cdot e_{\perp}) n_{\alpha} + \frac{1}{2} \nu_{th,e} n_{\alpha}$$  \tag{5.17}$$

The flux of $\gamma$ electrons due to secondary emission has the following form \[105\]:

$$\Gamma_{\gamma} \cdot e_{\perp} = -(1 - a_e) \sum_p \gamma_p (\Gamma_p \cdot e_{\perp})$$  \tag{5.18}$$

$\Gamma_p$ is the flux of the heavy particles of type $p$ and $\gamma_p$ is the secondary electron emission coefficient for an impact of the same type of heavy particles on the interface. The term $(1 - a_e)$ is included to cancel the term when the electric field is directed away from the interface. The sum of the two fluxes (5.17) and (5.18) is used as the boundary condition for the total electron flux.

5.3 Discharge evolution in time

For the terms breakdown process, breakdown moment and breakdown voltage we use the same definitions as those given in the previous chapter. Their respective definitions from the experimental point of view still hold in case of simulations: the breakdown process is a gradual phenomenon where a particular body of gas is turned into plasma when a significant amount of energy is introduced into the system, in our case through the electric field imposed by a system of electrodes. The breakdown process ends at the breakdown moment, when conducting current starts flowing through the gas and the voltage across the electrode gap drops. The voltage amplitude associated with the breakdown moment, just before the sharp voltage drop, is called the breakdown voltage. In simulations, we define the breakdown moment as the moment when the current in the electrodes starts rising exponentially. A simulation is considered terminated as soon as the breakdown moment is reached.

It has been experimentally shown in chapter 4 that in our geometry the AC-driven discharges develop over several voltage cycles. The light emission in 0.7 bar argon discharges can be observed over an increasing number of cycles as the frequency of the driving voltage increases. The time needed for the breakdown process is also not constant. The measurements we refer to and compare our simulation results with have been made with the aid of UV irradiation; we
**Figure 5.2:** $n_{Ar^*}$ at different points in time during the breakdown process at 60 kHz (left column) and 400 kHz (right column) discharges. Only a part of the geometry is shown: 7 mm between the electrode tips and 2.25 mm around the symmetry axis. The symmetry axis is positioned at the bottom of every frame. Metastable densities are expressed on a logarithmic scale to better show the particle distribution. The timing of every frame is given in a column next to the frames.
Figure 5.3: Particle densities averaged over the whole computational volume as a function of time. The graphs show electron, metastable, atomic and molecular ion densities together with the voltage form at the active electrode. The upper graph represents the breakdown process at 60 kHz and the lower one at 400 kHz voltage frequency. The graphs also show the timing of each frame in the figure 5.2. Every frame except the last one at each frequency was taken at the zero-crossing of the voltage.

have argued extensively that the most important role of UV irradiation in this case was the minimization of the statistical lag time, and that there were no significant modifications of the breakdown process (chapter 4).

At 60 kHz, the part of the breakdown process we were able to observe experimentally took less than one voltage cycle, and the development of a charged channel to cross the electrode gap took just a fraction of the last part
of the last voltage cycle, just before breakdown. An accumulation of the charge at the electrode tips in the beginning of the breakdown process was observed as point-like light emission. The maximum frequency at which we have observed the breakdown process by means of an iCCD camera was 800 kHz, and at that frequency the visible part of the breakdown process took $33.5 \pm 5$ voltage cycles. The discharge growth was not restricted to just one last cycle, but spread over multiple voltage cycles, with a diffuse structure growing from the electrode tips, but not bridging the electrode gap in the time between two successive zero-crossings of the driving voltage.

Figure 5.2 shows moments in the simulated discharge development at 60 and 400 kHz. The breakdown process is represented by the evolution of argon metastables density. Light emission observed in the experiments as shown in chapter 4 cannot be directly linked to any particle density. However, the emitted light came mainly from radiative processes in the plasma, and the light intensity is proportional to the density of the species involved. Given the low ionization degree and the fact that the wavelengths observed in the experiment were in the visible and near-visible region, atomic metastables are good candidates for the task at hand. One could argue that the dynamics of the ion density would give different results because they are subject to drift, while the metastables only diffuse, but this would not be a correct assumption. As can be seen in figure 5.3, the atomic ion density is very low, because of the very efficient collisional process between argon ions and neutral atoms that associates an argon ion and an argon atom into a molecular ion. As the $\text{Ar}^+$ density is orders of magnitude below that of the molecular ions or metastables, the contribution to the light emission made by the atomic ions would be negligible. The molecular ions, on the other hand, do not have large drift distance, as will be shown later in the text. It is, therefore, safe to assume that the atomic metastable density is a good representative of the simulated breakdown process.

Every frame shown in figure 5.2 except the last pair was taken at a zero-crossing of the driving voltage. The timing of each frame presented in figure 5.2 is shown in figure 5.3. This choice is suitable to show the differences in the discharge growth in the two frequencies, because at zero-crossings the production of the charged particles is virtually zero, as the electric field across the gap is very small. Consequently, there is no processes that can quickly change the appearance of the discharge in the vicinity of the zero-crossings, which makes them a sort of stable points in which one can compare the results.
of two discharges of very different growth dynamics.

The left column of the figure 5.2 shows the discharge evolution in time at 60 kHz. There was no propagation further than the electrode tip until the very last minimum, which is in agreement with our experimental results. The 400 kHz discharge shows different behaviour. At 95 µs after the start of the simulation, the discharge has already started to propagate from both electrode tips. The subsequent two frames show further propagation and charge buildup in the channel at zero-crossing and a minimum before the breakdown moment. The density was high in the entire volume between the electrodes already 1/2 cycle before the breakdown moment. This is also in agreement with the experimental results shown in chapter 4 where we saw that the growth of the channel to cross the electrode gap took several voltage cycles. Both the 60 kHz and the 400 kHz discharges took more than one voltage cycle to form. The dynamics of the discharge growth when crossing the electrode gap was different in the two chosen frequencies, and it took only a small portion of the last voltage cycle in 60 kHz, but it was preceded by charge buildup at the electrode tips, which was necessary for the subsequent channel formation.

Figure 5.3 shows the evolution of particle densities averaged over the whole computational volume, at 60 and 400 kHz. One should notice from figure 5.2 that the main particle production sites and the places of highest particle densities are just in front of electrode tips. As the particle densities at these places are many orders of magnitude larger than in the volume away from the lamp axis, we can safely assume that the figures showing the mean particle density evolution in time actually reflects the dynamics at the electrode tips and subsequently in the region between them. The graphs in figure 5.3 show similar basic behaviour - the particle densities buildup in every half of every voltage cycle for both frequencies, until the electrode gap is crossed and breakdown takes place, as shown in figure 5.2. This is the key feature of AC discharges in this frequency range.

Figure 5.3 shows that the electron and atomic ion densities follow the phase of the voltage across the active electrode, while the molecular ion and metastable densities rise in a more gradual step-like manner. The electron and atomic ion densities depend on electron temperature, as they are mostly created in reactions that involve electrons (see table 5.1). The electron temperature can follow the electric field profile in this frequency range, so it is understandable that the reaction coefficients for these processes will oscillate with the electric field. While the electron and atomic ion production rates are
low, these particles can be lost in drift (electrons) or other reactions, creating other species, like the molecular ions. The densities of molecular ions and metastables depend among other on reactions that do not directly reflect the electron temperature, and therefore suffer no oscillations as a function of the voltage phase. There are no large losses as well because the metastables do not drift, the molecular ion drift is limited (see further in the text) and they do not diffuse far. Thus the two different behaviours of particle densities as a function of time.

5.4 Breakdown voltage and formative time as function of frequency

![Figure 5.4](image)

**Figure 5.4:** The time evolution of the electron and molecular ion densities averaged over the whole computational volume. The simulations shown in this graph were done at the same voltage amplitude of 1.75 kV.

The experiments have shown that the breakdown voltage is a function of frequency. More specifically, the increase of frequency lead to a lowering of the breakdown voltage across the whole frequency range used in the experiments.

As finding the minimum voltage (the threshold voltage) needed for breakdown in simulations is an extremely long-lasting process, especially in high frequencies, we have decided to compare the characteristic voltages needed
for breakdown in a different manner. Two different ways of comparing the breakdown processes were used - first, using a unique voltage amplitude and comparing the formation time at several frequencies and second, finding the voltage amplitudes at which breakdown in different frequencies takes equally long.

The voltage amplitude and the formation time taken as a reference value was obtained from simulating breakdown in 60 kHz, using a slow voltage ramp, to find the true threshold voltage for the simulated breakdown process. We found that the threshold voltage was 1.75 kV and that the formation time was roughly 100 µs. One should note that choosing any value below 1.75 kV for simulating a 60 kHz discharge does not result in breakdown, as 1.75 kV was the lowest voltage amplitude at which the charged particle (mainly electron) production is bigger than the combined recombination, drift and diffusion losses.

Figure 5.4 shows the development of the electron and molecular ion densities at the same voltage amplitude (1.75 kV), for four different frequencies. We found that the time needed for breakdown decreases with the increase of frequency, which corresponds to the behaviour found when using an increasing amount of overvoltage [7]. The times needed for breakdown were 95.7 µs, 73 µs, 24.4 µs and 12.7 µs for 60 kHz, 100 kHz, 400 kHz and 1 MHz, respectively. This
behaviour at the same voltage amplitude suggests that the threshold voltage needed for breakdown decreases with the increase of frequency.

The alternative way to compare breakdown events at different frequencies is to find the voltage amplitudes for which the breakdown times were the same. The voltage amplitudes for 100 µs breakdown processes were 1.75 kV, 1.72 kV, 1.6 kV and 1.55 kV for 60 kHz, 100 kHz, 400 kHz and 1 MHz, respectively. Figure 5.5 gives a comparison between the experimental and simulation results at the same conditions. The values obtained in simulations show the same falling trend with the increase of frequency and similar values as found in the experiments, even though the breakdown voltage seems to drop more slowly with the increase of frequency in the simulations. This, however, does not necessarily mean that the simulations are giving incorrect results. In chapter 4 we have shown that the breakdown process takes longer in higher frequencies. Therefore, if we would have allowed for more than 100 µs for the discharge development in the model, the voltage amplitude necessary would have been lower at higher frequencies, and the slope in figure 5.5 would have been more like the one obtained in the experiments. The low values coming out of simulations on the low frequency end of the graph are probably an effect of overestimating the secondary electron emission coefficient of the molecular argon ions. These ions have very low energies and it is possible that our value of 0.04 is an overestimate. However, we made this estimate according to the data we had, as already explained in section 2, and we did not want to tailor the value to make the results fit better with the experimental data.

5.5 Effect of secondary electron emission

We have been studying AC breakdown processes that are relatively long compared to the breakdown events using fast-rising pulsed voltage. Some additional parameters become important as the long breakdown times of 100 µs allow for drift and diffusions of ions and secondary electron emission from the electrode surfaces. Figure 5.6 depicts the influence of the secondary electron emission by metastable and atomic ion impact. For this set of simulations, we have changed the value of secondary electron emission coefficient for metastables and atomic ions ($\gamma_{\text{Ar}^\ast}$ and $\gamma_{\text{Ar}^+}$, respectively) from 0.07 used in all the other simulations, to zero. The decision to make such a drastic change in the values of $\gamma_{\text{Ar}^\ast}$ and $\gamma_{\text{Ar}^+}$, and to do it at the same time, was made to show that
the secondary electron emission by these two particle types is relatively unimportant. The figure 5.6 shows that disabling the secondary electron emission by metastables and atomic ions does not change the timing of the breakdown process significantly, and it certainly does not hinder it. The reason for this is very simple - the metastables are not charged and therefore do not drift back and forth around the electrode tip, they just drift away from the production site. The atomic ions are depleted by the collisional process with neutral atoms, to produce molecular ions. Therefore, their low density (see figure 5.3) causes a low flux to the electrode and consequently makes the associated secondary electron emission rate negligible when compared to the same effect caused by the molecular ions.

The influence of the secondary electron emission by molecular ions is much stronger. They are numerous because of the production process that creates them is very efficient in near-atmospheric pressures. In a case when the secondary electron emission by the molecular ions is disabled (changed from $\gamma_{Ar^2}=0.04$ to zero), the breakdown process cannot be sustained at the same
Figure 5.7: Evolution of the axial density of molecular ions in the first cycle of a 60 kHz discharge, at 1.75 kV. The density is given on the symmetry axis between the electrode tips - the tip of the active electrode is at position zero, and the tip of the grounded electrode is at 7 mm. The inset shows the voltage amplitude on the active electrode during the collection of data. The lines in the graph are 1/50 of the voltage cycle apart. The red lines represent the evolution of the molecular ion density during the positive half-cycle, and the black ones during the subsequent negative half cycle.

voltage. Therefore we have to conclude that their role in an AC breakdown process in our geometry and frequency range is crucial.

Figure 5.7 shows the molecular argon ion density at the symmetry axis during one voltage cycle. The graph shows the behaviour of the Ar$_2^+$ density in the first simulated voltage cycle at 60 kHz. The lines in the graph are 1/50 of the voltage cycle ($3.33 \times 10^{-7}$ s) apart. The active electrode is situated on the left-hand side, the grounded one on the right.

As the voltage on the active electrode starts rising in the first half of the voltage cycle, a sharp increase in particle density occurs at the tip of the active electrode. This charge buildup is followed by the drift of the molecular ions away from the electrode tip, as can be seen from the position of the maximum of the particle density moving towards the center of the electrode gap. The drift is caused by the high electric field at the positively charged active electrode. Subsequently, as the polarity of the voltage on the active electrode changes, the molecular ions drift back to the electrode surface, striking it and creating secondary electrons.
Figure 5.8: Evolution of the axial density of the molecular ions in the 60 kHz breakdown process, at 1.75 kV. The density is given on the symmetry axis between the electrode tips - the tip of the active electrode is at position zero, and the tip of the grounded electrode is at 7 mm.

At the same time, the drift of the electrons is directed towards the grounded electrode, where they enter the high electric field region around the tip of the electrode and initiate the ionization and excitation processes that ultimately lead to the creation of new molecular argon ions near the tip of the grounded electrode. This can also be seen in the graph.

The losses of molecular argon ions during one voltage cycle, in which they drift back and forth from the electrode tip is not constant, but a function of frequency. We compared the losses in the second voltage cycle after the beginning of the simulation for the simulations done at the same voltage amplitude of 1.75 kV. The losses were 61%, 59%, 48% and 42% for 60 kHz, 100 kHz, 400 kHz and 1 MHz, respectively.

Figure 5.8 shows the molecular argon ion density at the symmetry axis in the whole 60 kHz breakdown process. One can see that in every voltage cycle there is efficient particle production, drift towards the center of the electrode gap, followed by the drift back to the electrode surface, at lower density. The arrow in the figure shows the direction of time. As the breakdown moment approaches, the central ion density grows as well, although the distribution is always symmetric with respect to the center of the electrode gap. This is another way to show that at 60 kHz there is no formation of the charged
Figure 5.9: Evolution of the axial density of the molecular ions in the breakdown process, at 1.75 kV, at 100 kHz, 400 kHz and 1 MHz. The density is given on the symmetry axis between the electrode tips - the tip of the active electrode is at position zero, and the tip of the grounded electrode is at 7 mm. The lines in the graphs are 1/25 of voltage cycle apart: 0.4 µs at 100 kHz, 0.1 µs at 400 kHz and 0.04 µs at 1 MHz.
channel that would extend in one chosen direction from an electrode tip, before the very last part of the very last voltage cycle.

Figure 5.9 shows the same for 100 kHz discharges, but tells a different story about the discharge formation at higher frequencies. The asymmetric distributions of the molecular argon ions that occur after several voltage cycles at 400 kHz and 1 MHz show that there is partial discharge growth in the direction of the other electrode, and that it is initiated from both electrode tips, in several last voltage cycles. This is in very good agreement with the experimental results shown in chapter 4 where we observed no formation of the charged channel in the gas volume before the very last voltage cycle before breakdown moment at lower frequencies (60 to 220 kHz), but such observations were made at higher frequencies (400 to 800 kHz).

The molecular ion densities are very low in the central part of the electrode gap for low frequencies - 60 and 100 kHz, because the discharge does not partially propagate before the bridging of the electrode gap. When the gap is bridged, just before the breakdown moment, the central molecular ion densities rise to $10^{21} \text{m}^{-3}$, just like it can be seen in the profiles belonging to the 400 kHz and 1 MHz simulations. The reason why this happens earlier in the breakdown process in higher frequencies is partial bridging of the gap during the voltage cycles before the last one, which can be seen also in the experiments.

5.6 Discussion

In this chapter we presented results of simulations in 0.7 pure argon atmosphere using AC driving voltage. The simulations were done using a two-dimensional fluid model and a cylindrically symmetric geometry. The aim of this chapter was to make an overview of most important characteristics of the AC discharges in the frequency range where the discharge takes more than a single cycle to form and the electron losses are still drift dominated.

The model we used was adapted to describe the experimental conditions of which we gave an account of chapter 4. The discharges in the given experimental conditions were gas volume discharges that grew in the space between the electrode tips, which made it possible to model them in a 2D cylindrically symmetric geometry. The simulation results presented in this chapter are in good agreement with the experimentally observed data (chapter 4) in several important respects - the appearance of the discharge, its behaviour as a func-
tion of frequency and the effect of change in frequency has on the minimum voltage needed for breakdown. The results presented in the previous section allowed us to explain two phenomena that were thus far explained in a way that was not satisfactory in our experimental conditions or not explained at all. These are presented in the following two subsections.

5.6.1 A lower threshold voltage for AC-driven discharges

The evolution of the particle densities takes multiple voltage cycles, which is essentially the reason why the AC-driven breakdown processes require lower threshold voltage than the pulsed breakdown in the same experimental conditions. First, the discharge is allowed a longer time to form. It has been shown many times that the formation time for the discharge is a steep function of the used overvoltage \[7, 121\], as the first Townsend ionization coefficient is an exponential function of the applied electric field. From the experimental data \[121\] it can be seen that the discharge formation time is a bijective function of the overvoltage. If we make an additional assumption that the published data reflects a unique law that connects the formation time to the overvoltage, we are allowed to assume the reverse function, one that would connect the overvoltage to the discharge formation time. In this function, the overvoltage would decrease as the formation time increased. From this, we can draw a conclusion that the more time we allow our discharge to form, the lower the voltage that we have to supply. This has already been shown in pulsed-voltage experiments by changing the pulse slope, as shown in chapter \[2\]. Our AC discharges take as much as three orders of magnitude longer to form, and therefore can be expected to require lower voltage.

Another, more important reason why the AC breakdown processes require lower voltage than their pulsed equivalents is that the voltage changes polarity while the discharge forms, allowing for additional phenomena to help with the charged particle production. The heavy charged species in AC-driven breakdown processes drift back and forth around the electrode tips, making the secondary electron emission from electrode surfaces an important source of electrons. In our case, molecular ions are key species responsible for secondary electron emission. This effect allows for an effectively higher production of charged particles than is the case in an unipolar fast discharge, even though the electron losses in this frequency range are substantial. In pulsed discharges, secondary electron emission is not likely to play any role, because the heavy
particles are effectively immobile during the entire breakdown event. This has been demonstrated in chapter 3.

5.6.2 Lowering of the breakdown voltage with increase of frequency

The experiments described in chapter 4 have shown that the threshold voltage needed for breakdown decreases with the increase of frequency. This phenomenon is also an effect replicated in the simulations and it has not been previously explained in a satisfactory way, at least as far as our experimental conditions are concerned. Two possible explanations were offered. First, there was a possibility that the electron drift losses were lowered with the increase of frequency [9] - we have already shown in chapter 4 that the electron drift losses were still very large in the whole frequency range we used, because the electron drift distance in one half of a voltage cycle was much larger than was the length of our electrode gap. There was certainly some lowering of the electron drift losses over the entire frequency range we used, since it spread over 1.5 orders of magnitude, but this effect alone cannot explain the effects we have observed on its own. We do expect the lowering of the electron drift losses to become significant with further increase of the voltage frequency.

Second, a conjecture was made that due to the high electron drift losses and low ion mobility, positive net charge would form in the electrode gap away from the electrodes, modify the electric field and allow the starting of an avalanche process at lower voltages as the frequency increased [9]. In our experimental and modelling conditions, we do not believe that this effect had a noteworthy influence on the discharge development. There are several reasons for this. One, we see the lowering of the threshold voltage in the frequency range between 60 kHz and 220 kHz, as well as in higher frequencies. The peculiarity of this lower frequency range is that the formation of the channel to cross the electrode gap happens in one voltage cycle or less, and that the charged channel starts growing from an electrode tip. There is, therefore, no reason to assume "islands" of high charge density in the electrode gap away from the electrode tips, which would start avalanches somewhere in the gas volume. The reason for the lowering of the breakdown voltage must be something else than charge accumulation in the electrode gap.

In addition, we have observed in the simulations that there really exists a threshold voltage under which the particle densities do not rise, the particles do not multiply and the breakdown can never occur, and that this voltage
AC breakdown - Simulations

is a function of frequency. For example, a simulation of 400 kHz or 1 MHz discharge will result in breakdown at voltage amplitude of 1.6 kV. The same voltage amplitude at 100 kHz and 60 kHz will not be sufficient for charge buildup and eventual breakdown. We would like to focus on the beginning stages of the simulations, where there is still no high particle density of any species and the voltage has not gone through a phase cycle yet, making it impossible for the ions to drift back and forth in the electrode gap and create islands of high density. Even in these early stages in the simulations, there is a clear difference between the discharges at different frequencies, where some will subsequently grow and develop in at a given voltage amplitude, and some not. We do not believe that the reason for this is the chemistry of the processes. At these frequencies, in a 0.7 bar argon atmosphere and a low ionization degree, the electron energy is given by and can follow the phase of the imposed electric field. Therefore, the electron energy is independent of frequency at the start of the simulation in our frequency range, and the starting reaction rates in the simulations are thus also independent of frequency.

The suggestion that the net charge buildup in the electrode gap is responsible for the lowering of the threshold voltage as the voltage frequency increases is, thus, not a satisfactory explanation for our observations. Besides, we were experimenting and modelling a pin-pin electrode system. The net charge needed to modify the electric field already given at the electrode tips is very high and can possibly be achieved very late in the breakdown process, after the particle densities have sufficiently increased. This effect would possibly be able to speed up the breakdown process long after it has already started, but not influence it from the beginning.

There is still an effect that causes the threshold voltage needed for breakdown to drop with the increase of frequency. We believe that the solution to this problem lies in the behaviour of the molecular ions in a single voltage cycle. As has been shown in figures 5.7, 5.8 and 5.9, the molecular ion density oscillates back and forth around the electrode tip as the phase of the voltage on the active electrode changes. In these oscillations, the molecular ions undergo collisions with other species in the plasma and their density decreases as a result. The decrease in a single voltage cycle is a function of frequency, simply because in higher frequencies there is less time available between the equivalent points in two subsequent voltage cycles for the collisionally-induced losses. Higher frequency, thus, means less molecular ion losses, and higher density to drift back to the electrode tip and induce secondary electron emission.
We have just explained how an increase of frequency can give an effective increase of electron production. The lowering of the electron losses that are drift-dominated with the increase of frequency is not considered a noteworthy contribution, but even if it was, this effect would add to the increase of the net electron production in a single voltage cycle. The total production rate of electrons can, therefore, be separated in two parts - the part that is caused by the chemistry in the breakdown process, and the part caused by the secondary electron emission. If we assume that at the threshold voltage for breakdown process one must have a certain constant minimum of the net electrons produced in a given time interval, and we know that the increase of frequency increases the part caused by the secondary electron emission, it is clear that the part caused by the chemistry can be lowered. The lowering of the contribution of the chemistry can be achieved by lowering of the mean electron energy via the imposed electric field. This is why the breakdown processes at higher frequencies are possible at lower voltages.

5.6.3 Outlook

We have shown that the simulations done on the HID lamp system and 0.7 bar argon using AC voltage gave results that are in very good agreement with the experiments presented in chapter 4. There are, however, several ways in which the model we used can be improved. The size of the computational cells in the model is a concern. The geometry should not be excessively coarse, because that would cause errors in the calculations of various key parameters, such as the electric fields in the system. On the other hand, very small size of computational cells would cause very long calculation times, especially at high frequencies. The implementation of the local grid refinement would greatly help this issue.

Additionally, the chemistry used in the model may not be sufficiently complex for the description of a breakdown process in near-atmospheric pressure. A possible improvement would be the addition of another effective atomic metastable state that would represent the \((4p)\) and higher-lying excited states in the argon atom. Excimer molecules could be added as well. This would give a more correct effect of the excited species on the breakdown process.
5.7 Conclusion

This chapter has shown the results of two-dimensional fluid model simulations of AC breakdown in 0.7 bar argon atmosphere. We have used a two-pin electrode system enclosed in an HID lamp geometry with fixed length (7 mm) of the electrode gap. The electrode gap and the gas pressure fixed, we were able to distill the effect of the voltage frequency (60 kHz to 1 MHz) in the overall breakdown process. We have shown its effect on the appearance of the discharge, the threshold voltage needed for breakdown and the timing of the breakdown process. The results of the simulations are in good agreement with the experimental data shown in chapter 4, both in their qualitative behaviour as function of frequency, as in their quantitative behaviour in terms of breakdown voltages and formative times. We have also demonstrated the importance of the secondary electron emission from electrode surfaces, in particular by molecular ions, in the breakdown process and linked it to the lowering of the threshold voltage with the increase of frequency observed both in experiment and model.
Statistical time lags in AC discharges

Abstract. The chapter presents statistical time lags measured for breakdown events in near-atmospheric pressure argon and xenon. AC voltage at 100, 400 and 800 kHz was used to drive the breakdown processes, and the voltage amplitude slope was varied between 10 and 1280 V/ms. The values obtained for the statistical time lags are roughly between 1 and 150 ms. It is shown that the statistical time lags in AC-driven discharges follow the same general trends as the discharges driven by voltage of monotonous slope. In addition, the validity of the Cobine-Easton expression is tested at an alternating voltage form.

6.1 Introduction

The breakdown process in gasses is a phenomenon that features gradual changes as the transition from the gaseous to the plasma state occurs. For a successful breakdown it is necessary to supply enough energy to the gas gap to initiate electron avalanches; this is usually done by placing the gas gap in an electrode system, thus creating an electric field that gives energy to free electrons. In the case of high pressures and moderate to large electrode gaps, the breakdown process features a growth of thin, ionized channels. The development of the ionized channels is followed by the bridging of the electrode gap, building up the channel conductivity and finally a sharp drop of the potential difference between the electrodes. This point in time is known as the breakdown moment. The potential difference across the gas gap associated with the breakdown moment is called the breakdown voltage.

The breakdown process is considered to be a statistical process because it has some degree of uncertainty associated with it, that is to say it does not happen in the exact same manner every time. Consequently, the time it takes from the onset of the voltage to the breakdown moment changes from one breakdown event to another. This time is called the total time lag and it consists of two parts - the statistical time lag and the formative time lag.

The part of the breakdown process starting from the first electron multiplication that will lead to breakdown until the breakdown moment is called formative time lag. Ideally, the breakdown process in the gas starts at the exact same moment at which a sufficiently high electric field is brought to the gas gap. However, this would require an abundance of free electrons in the gas gap, to ensure that at least one of them would start an electron avalanche that would lead to breakdown. In reality, there is a delay between the onset of the electric field and the start of the formation process, due to the absence of free electrons in the region of adequate electric field strength. This delay is called the statistical time lag. The statistical time lag comprises of two main parts: the time spent on waiting for a free electron to appear in the electrode gap and the time it takes to start an avalanche process that will lead to breakdown.

Formative time lags have been examined for pulsed breakdown processes in low pressure and for a number of gasses \cite{120,121}, as a function of the overvoltage and experiment repetition frequency or the afterglow time. It was found that the decrease in the overvoltage used to drive the breakdown process causes an increase in the formative time lag. This is due to the specific form...
of the Townsend’s first ionization coefficient $\alpha$ as a function of the reduced electric field $E/p$ \[7\]

$$\alpha/p = A \exp(-Bp/E) \quad (6.1)$$

$p$ is the pressure and $A$ and $B$ are coefficients specific for the gas type. The ionization coefficient is a steep function of the reduced electric field. The amplification of the number of electrons in an avalanche exponentially rises with $\alpha$ \[7\]. Even a very small increase of the electric field above the threshold value is thus sufficient for a large reduction of the formative time lag.

Experimental studies of statistical time lags have been conducted in a broader set of conditions than just the considerations on the formative lag, but still mostly in low gas pressures \[9,125–130\]. It has been observed that the increase in the overvoltage applied across the gas gap causes a decrease in the statistical time lag. This means that the number of electrons required to start a successful breakdown process decreases with the increase of the reduced electric field in the gas gap. It also shows that one electron is not always sufficient to start a successful breakdown process, otherwise the statistical time lag would be independent of the overvoltage. This result was anticipated by Wijsman \[131\] in 1949. He developed an analytical formulation of the probability $P(n,d)$ that one electron causes an avalanche of $n$ electrons at distance $d$ from the electrode

$$P(n,d) \approx \left(\frac{1}{\bar{n}}\right) \exp\left(-\frac{n}{\bar{n}}\right)$$

$$\bar{n} = \exp\left(\int_0^d \alpha(x)dx\right) \quad (6.2)$$

This probability is exponentially decreasing with the number of electrons in the avalanche $n$. He also gave a probability $P_0$ that the succession of avalanches goes indefinitely, i.e. that the avalanche will lead to breakdown

$$P_0 = \begin{cases} 0 & , q < 1 \\ 1 - 1/q & , q > 1 \end{cases}$$

$$q = \gamma(\bar{n} - 1) \quad (6.3)$$

$\gamma$ is the secondary electron emission coefficient for ions in the breakdown process. If one wishes to determine the probability of breakdown as a function of the applied voltage, one should know $q$ as a function of voltage. In general, $q$ increases rapidly with the reduced electric field in the region above the breakdown value, again due to the specific form of the Townsend’s first ionization coefficient as presented in equation \[6.1\]. As a result, the statistical time lag
indeed decreases very quickly with just a small increase in the electric field in the gas gap.

It has also been shown from the experiments varying the afterglow time, that the statistical time lag depends on the amount of pre-ionization. The more charged particles remain from the previous discharge, the shorter the statistical time lag. Related to this, the presence of UV irradiation or radioactive materials as well as the increase of the electrode gap were observed to have a decreasing effect on the statistical time lag because of the increased probability of the appearance of an electron to initiate the discharge [9].

Zuber and von Laue developed a theory in 1925 [132,133] that deals with the structure of the total time lag. The theory involves several parameters important for the characterization of the time lag, such as the rate at which the electrons are produced in the gap by an external ionizing agent $\beta$, the probability of an electron appearing in a region of the gas gap where it can start an avalanche $p_1$ and the probability that such an electron will indeed lead to breakdown $p_2$. The number of breakdowns that occur in the time interval $t + dt$ is

$$dn = -\beta p_1 p_2 n_t dt$$

$n_t$ is the number of breakdowns with time lags greater than $t$. Integration over the whole time interval $[0, t]$ gives

$$\ln(n_t/n_0) = -\int_0^t \beta p_1 p_2 dt$$

$n_0$ is the total number of time lags observed. Assuming that parameters $\beta, p_1$ and $p_2$ do not change with time, the equation above can be expressed as

$$n_t = n_0 \exp(-\beta p_1 p_2 t) = n_0 \exp(-t/\sigma)$$

According to the statistical theory, $\sigma$ is the mean time lag. It can be easily approximated to the mean statistical time lag, providing that the formative lag in the experiment is small compared to the total time lag.

The work of Zuber and von Laue has been proven valid in a number of experiments, but its limitation lies in the fact that the parameters $\beta, p_1$ and $p_2$ are presumed to be constant in time. When voltage is varied in time, these coefficients vary with it. It has been experimentally determined by Cobine and Easton [134] that equation 6.6 can best be modified to the following empirically obtained form

$$n_t = n_0 \exp(-bt^c)$$
Parameter $c$ can be higher or lower than unity, depending on the slope of the voltage across the electrodes. For example, when the voltage is decreasing, $c$ is less than unity. This has been explained in the following way: the longer the time lag, the lower the voltage across the gap when a free electron appears in the volume. This causes a lower probability that the electron will lead to breakdown. As a result, an electron arriving late is less likely to cause breakdown than the electron arriving early in the experiment. Therefore, a greater number of the time lags fall in the long time range than would be the case at a constant voltage. In the case when the voltage across the gas gap increases during the experiment, the result is the opposite, $c$ is greater than one.

Statistical time lags in high pressure argon and xenon discharges were examined in this study for their importance in the lighting industry. While the formative lag in high intensity discharge (HID) systems is of the order of microseconds ([121] and chapter [4]), the statistical lag can be orders of magnitude larger and have a large spread of values. This is of particular interest for lamp driver design.

In this chapter we show measured values of the statistical lag as a function of gas type and pressure, electrode gap, frequency and voltage amplitude slope for high frequency AC breakdown in argon and xenon. We also test the validity of the theory presented by Zuber and von Laue [132,133] and later adapted by Cobine and Easton [134], on the structure of time lags during breakdown in gasses. We show that their theories, although developed for quite different voltage forms, still hold for high-frequency AC breakdown, provided that one additional parameter is introduced.

6.2 Details of the experiments and the analysis

6.2.1 Experimental parameters

Setup details were given in chapter [4] and will be shortly presented in this section. We used a pin-pin electrode geometry enclosed in 70 W Philips YAG (Yttrium Aluminium Garnet) burners as designed for metal-halide HID lamps. The electrodes were rod-shaped, with 0.6 mm diameter, forming an electrode gap of 4 or 7 mm. The volume of the lamp burners was $3.6 \times 10^{-7}$ m$^3$. They were filled with 0.3 or 0.7 bar of argon or xenon, without the addition of salts.
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Table 6.1: Lamp types used in the experiments. A lamp type is one specific combination of gas type, pressure and electrode gap.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pressure [bar]</th>
<th>Electrode distance [mm]</th>
<th>number of available lamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>0.3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Xe</td>
<td>0.3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

or mercury.

The experiments were done using a high-frequency sine voltage signal with linearly rising amplitude on the active electrode, while the second electrode was grounded. The AC signal was generated in a way which enabled the change of frequency between 100 kHz and 1 MHz and the slope of the voltage amplitude between 10 and 1280 V/ms. We performed breakdown voltage measurements for each breakdown process, using a high voltage probe and an oscilloscope. Breakdown voltages were measured for different frequencies and voltage amplitude slopes.

Several lamps were made and measured for each lamp type (lamp type in this case denotes a single combination of gas type, gas pressure and electrode gap) to avoid our measurements being influenced by possible defects in electrodes, burners, errors in lamp filling or sealing procedure. The list of lamp types used in the experiments is given in table 6.1. Ten breakdown voltage measurements were performed for each lamp in table 6.1 and for each data point. One data point is a specific combination of the voltage frequency and the slope of the voltage amplitude. The average values and the standard deviations were calculated for each lamp, and subsequently for each lamp type. Data points in the graphs throughout this chapter represent the average values and the standard deviations for the corresponding lamp type.

Experiment repetition frequency was held constant at 0.1 Hz. This choice
provided sufficient time between two breakdown processes for them not to influence each other. Our experimental systems contained only noble gasses and the discharges were not allowed to burn after breakdown, which ensured that no gas heating would take place. A current limiter was used to ensure that the power to the lamps is cut off after breakdown, as described in chapter 4. The dielectric surface of the lamp burner in which we have enclosed our experimental system was, however, very likely to have been charged during one breakdown process and still remained charged during the next one, due to the very long decay time of charge on dielectric surfaces. However, we found this to be an acceptable starting condition for two reasons. First, the discharges in our geometry do not develop on the burner surfaces, as has been shown in chapter 4. The charges on the surfaces are, thus, not actively participating in the discharge development. Second, the starting conditions were the same for each breakdown event, or similar to the point that we could not distinguish one from another. We know this because during the measurements we did not observe a systematic change in the breakdown voltage. Large changes in the amount of free electrons in the gas volume where the electric field was high enough to sustain an avalanche process would have changed the outcome of the breakdown voltage measurements. Even if the changes of the surface charge were gradual, breakdown voltages would gradually change over time. Nothing similar was observed.

Breakdown processes were at times aided by a flux of UV irradiation at 254 nm. Between $10^{13}$ and $10^{14}$ photons entered the lamp volume every second, and about 5% of those hit one of the electrodes. With the estimated efficiency of $10^{-3}$ for photoelectric effect on the cathode [7], the UV irradiation ensured the emergence of between $5 \times 10^8$ and $5 \times 10^9$ electrons per second in the lamp volume. Consequently, the preionization levels were high enough to minimize the statistical time lag. This assumption will be later supported in the results section of the chapter. Another function of UV irradiation in these experiments was to remove the charge from the surfaces of the lamp burner. This effect has been discussed already in 1981 [119]. The lack of charge on the insulating burner surfaces in the case of UV-assisted breakdown is an essential difference between the UV-aided and non-aided breakdown events in the case where the discharges develop on the insulating surfaces. However, as the discharges in our experiments did not develop on the dielectric surfaces (shown in chapter 4), this effect is not considered important.
6.2.2 Determination of statistical time lags

The procedure of determining the statistical time lag in AC breakdown required a comparison of the breakdown voltage of non-assisted with UV-aided breakdown processes. The idea is illustrated in figure 6.1. Our experiments were done by using a sine voltage with a linearly rising amplitude. In the first part of the voltage signal, denoted as 1 in the figure, the voltage is too low to start an electron avalanche in the lamp. At the transition from part 1 to part 2, the voltage crossed the threshold at which the reduced electric field in regions of the lamp became high enough to initiate an electron avalanche. At this point it became possible to initiate the discharge formation near the electrode tips which subsequently lead to breakdown. However, the preionization levels in non-aided breakdown events were very low, which caused an appreciable statistical time lag to occur, while the voltage amplitude was still rising in a linear manner. This portion of the breakdown process is denoted as 2 in the figure. Finally, at the transition from part 2 to part 3, an avalanche started
that later lead to breakdown. The final part (part 3) of the process is therefore the formative time lag.

The influence of UV irradiation on the breakdown process was already discussed at length in chapter 4. It was concluded that the following two aspects have a notable influence on the breakdown process. First, the statistical time lag in UV-assisted measurements was expected to be negligible. Therefore, the part 2 in the voltage form shown in figure 6.1 does not exist for the UV-aided breakdown. The formation of the avalanches that leads to breakdown takes place after the voltage amplitude crosses the threshold value for sustaining the breakdown process. This is why the UV-aided breakdown takes place at lower voltages, which leads to the second UV-related effect with notable influence on the breakdown process. The formative time lag was expected to be prolonged because the breakdown process took place at lower voltages. We will show that even the prolonged formative time lag in UV-aided breakdown process as reported in chapter 4 is still orders of magnitude lower than the statistical time lag encountered in the non-aided case, and can be neglected in the calculations.

As stated before, by comparing breakdown voltages of UV-aided with the corresponding non-aided breakdown processes, the statistical time lag in the non-aided breakdown events can be derived. Let \( T_0 \) represent the time interval denoted as part 1 in the figure 6.1 when the electric field in the gap is too low to sustain a breakdown process. \( T_s \) is the statistical time lag and refers to the part 2, and \( T_f \) is the formative time lag and refers to the part 3 of the breakdown process as represented graphically in figure 6.1. \( T_f,UV \) is the formative time in UV-assisted case. The statistical time lag \( T_s \) is presumably present only in non-aided breakdown. The structure of the total time used for one breakdown event for non-aided (\( T_{tot} \)) and UV-aided (\( T_{tot,UV} \)) events can be represented in the following way

\[
T_{tot} = T_0 + T_s + T_f
\]  
\( T_{tot,UV} = T_0 + T_{f,UV} \)  

(6.8)  
(6.9)

The difference in the total time can give the statistical time lag, presuming that the difference in the formative times can be neglected when compared to the statistical lag, \( T_s \gg T_{f,UV} - T_f \)

\[
T_{tot} - T_{tot,UV} = T_s + (T_f - T_{f,UV}) \approx T_s
\]  

(6.10)

The total time can be expressed as the ratio between the breakdown voltage
Figure 6.2: Breakdown voltage measured as a function of the voltage amplitude slope, in UV-assisted and non-assisted breakdown events. The data shown belongs to the discharges in argon, at 0.7 bar and at 400 kHz. The inset shows the same data, only on a logarithmic x-axis. The same trends as shown in this graph were obtained at other gas pressures, frequencies and also for xenon.

\[ V_{bd} \text{ and the slope of the voltage amplitude } R \]

\[ T_{tot} = \frac{V_{bd}}{R} \]  \hspace{1cm} (6.11)

The statistical time lag can be expressed as a function of slope and voltage difference

\[ T_s = \frac{V_{bd} - V_{bd,UV}}{R} \]  \hspace{1cm} (6.12)

6.3 Breakdown voltage measurements

Figure 6.2 shows the measurements used to calculate the statistical lag in AC-driven breakdown processes. We compared breakdown voltage measurements for UV-assisted and non-assisted breakdown processes and calculated the time lags from the difference in breakdown voltages measured at the same frequency and the same voltage amplitude slope. For these calculations to be valid it is necessary for the UV-assisted breakdown to be virtually free of statistical lag and that the UV irradiation does not affect the discharge evolution in any other way.
Figure 6.2 shows that the statistical time lag is not only lowered, but virtually gone in the case of UV-aided events. This is evident from the difference in behaviour of the breakdown voltage as a function of the voltage amplitude slope. When the breakdown process was aided by UV irradiation, the breakdown voltage did not change with the slope, which was not the case in the non-aided breakdown events.

The link between the observed phenomenon and the assumption about the lack of the statistical time lag in UV-aided processes follows from figure 6.1. There, a portion of the voltage signal at the active electrode in the non-aided case is inefficiently used to wait for an electron avalanche that will subsequently develop into a full discharge. This part, designated as region 2 in the figure, causes statistical time lag. During this time the voltage amplitude keeps rising, due to its positive slope. The faster the slope, the more the voltage amplitude rises in the same amount of time. In an event where a breakdown process would not suffer from statistical time lag and where the formative time lag would be negligible, the measured breakdown voltage would be the threshold voltage amplitude needed for breakdown and the breakdown voltage would not change with the amplitude slope.

The contribution of the formative time lag to the increase of the breakdown voltage would be important in the case where the formative time lag would be large or in the case of fast voltage amplitude slopes. Formative time lags in our experiments were, however, very short. As shown in chapter 4, formative times rise with the increase in the voltage frequency. The longest formative times relevant to the calculations presented in this chapter were in argon at 0.7 bar and 7 mm electrode gap at 800 kHz, xenon at 0.3 bar and 7 mm electrode gap at the same frequency and xenon at 0.7 bar and 7 mm electrode gap at 400 kHz. Formative times for these discharges were 0.041 ms, 0.121 ms and 0.037 ms, respectively, for UV-aided breakdown. We take the values for the UV-assisted events as a reference because these formative times are expected to be longer than the corresponding formative time lags in non-assisted breakdown processes because they occur at lower voltage, as shown in chapter 4. At the highest voltage amplitude slopes at which the statistical time lags were calculated, the increase in voltage due to the formative time lags was 26 V, 39 V and 47 V, respectively. Such small increases in voltage fall within the error bars of the breakdown voltage measurements. In addition, all formative time lags were at least one to two orders of magnitude lower than the corresponding statistical time lags, as will be shown in the next section. The values were
measured as the time delay from the first light emitted from the electrode tip to the breakdown moment. Even if the formation time took twice as long, the formative time lags would still be small enough to be neglected in comparison with the statistical time lags.

In conclusion, our measurements have shown that the UV-aided processes were virtually free of statistical time lag, that the UV irradiation did not affect the discharge development in a way that would disallow us to compare the UV-aided and non-aided breakdown events (chapter 4) and that the formative time lags reported in chapter 4 were negligible compared to the corresponding statistical time lags. Consequently, the assumptions on which rests the validity of the procedure for determining statistical time lag as described in section 6.2.2 are satisfied for AC-driven breakdown events in our experimental conditions.

6.4 Statistical time lags

Figures 6.3 to 6.8 show the statistical time lags as a function of voltage amplitude slope, calculated at 100, 400 and 800 kHz. The bars in the graphs represent the standard deviation calculated for a function of multiple (two in our case) independent variables where each variable has a known variance.

The term overvoltage is used quite often in this chapter. It is associated with the excess voltage applied to the electrode, with respect to the threshold breakdown voltage at given conditions. If the threshold breakdown voltage is given by $V_b$, and the voltage at which the measurements are performed is $V$, then the difference $\Delta V = V - V_b$ is the overvoltage applied to the electrode.

It is usual [9,120,121,125,129] to show time lags as a function of overvoltage, not as a function of the slope of the voltage amplitude. It is also easier to relate the statistical time lag to voltage or electric field than to the voltage amplitude slope, because it is intuitively clear that the higher the electric field, the higher the probability that one electron will cause avalanches that will lead to breakdown [131]. Nevertheless, we chose to present our results as a function of the voltage amplitude slope because the voltage amplitude slope is a parameter which we were able to control very precisely in our experiments. In addition, even though the slope can be related to the overvoltage in a simple way, the interpretation of the results is not straightforward. Because of the reasons given, all the determined statistical time lags are presented as a function of the voltage amplitude slope. An extension to the scope of overvoltage
Figure 6.3: Statistical time lags for argon at 100 kHz, presented as a function of voltage amplitude slope. The inset shows the same data on a linear x-axis.

Figure 6.4: Statistical time lags for xenon at 100 kHz, presented as a function of voltage amplitude slope.
Figure 6.5: Statistical time lags for argon at 400 kHz, presented as a function of voltage amplitude slope.

Figure 6.6: Statistical time lags for xenon at 400 kHz, presented as a function of voltage amplitude slope.
Figure 6.7: Statistical time lags for argon at 800 kHz, presented as a function of voltage amplitude slope.

Figure 6.8: Statistical time lags for xenon at 800 kHz, presented as a function of voltage amplitude slope.
is presented in the next section.

Figures 6.3 to 6.8 show that the statistical time lag decreases as a steep function of the voltage amplitude slope. This is caused by different levels of overvoltage achieved at different voltage amplitude slopes during statistical time lags. The faster the slope, the more the voltage amplitude grows in a given time increment. The resulting overvoltage is higher for the faster rising voltage. Higher overvoltage causes a higher Townsend’s first ionization coefficient and results in more efficient electron avalanches. The probability of a successful breakdown greatly increases with the number of free electrons available in the electrode gap. This is a crucial factor in the behaviour of the statistical time lags, as we have discussed in the introductory section.

Statistical time lags in all given figures are always bigger in breakdown events at higher gas pressure and in xenon compared to the breakdown events in argon. The time lags do not appear to be a function of frequency. This is a result one would expect given that there is no transition between the drift-dominated to the diffusion-dominated mode in our experimental conditions, as we have shown in chapters 4 and 5. With further increase in frequency we would expect the statistical time lag to be lowered, as the electron loss processes become lower and diffusion-dominated.

The statistical time lags reaching 120 ms for the slowest slope (Ar at 0.7 bar and 4 mm electrode gap) are quite large compared to the values obtained for pulsed discharges [9]. However, given our slow voltage amplitude slope and the fact that we performed the measurements using high frequency AC voltage, we expected lower electric fields in the electrode gap and consequently larger statistical time lags.

A more interesting observation is that the statistical lag in shorter electrode gaps is larger than the corresponding lag in the larger gaps. As was explained in [9], increasing the gap length allows many more electrons to be produced in the gap by means of cosmic radiation or similar events responsible for the occurrence of first free electrons; this, in turn, reduces time lags. The effects are very clear for the difference in electrode gaps used in our experiments - reducing the gap from 7 mm to 4 mm effectively reduces the volume where the initial electrons have to be created by 50%.
6.5 Statistical time lags as a function of overvoltage

Time lags are usually presented as a function of overvoltage. This is understandable given the fact that they can be related to the Townsend’s first ionization coefficient, that greatly depends on the imposed electric field. The mean statistical time lag can be expressed \[ T_s = \frac{1}{YP} \] as

\begin{equation}
\bar{T}_s = \frac{1}{YP}.
\end{equation}

\(Y\) is the electron yield, and \(P\) is the probability that one electron will cause avalanches that will lead to breakdown. \(P\) was given in the introductory section in equation (6.3). This equation holds for low pressure discharges and in cases where the formative time lag is much smaller than the statistical time lag. While the latter condition was fulfilled in our experiments, we were dealing with high rather than low pressure discharges. This makes deviations from the theoretical predictions possible.

It is not simple to express statistical time lags as functions of overvoltage in our experiments for a simple reason that the overvoltage was changing during the statistical lag. One should recall that we were doing experiments with a sine voltage signal with a linearly rising amplitude. Nevertheless, time lags can be expressed as a function of the final overvoltage reached at the end of the breakdown process. This is done in figure 6.9 for argon discharges at 100 kHz. The overvoltage was calculated in the following way

\[ OV = \frac{V_{bd} - V_{bd,UV}}{V_{bd,UV}}. \]

\begin{equation}
OV = \frac{V_{bd} - V_{bd,UV}}{V_{bd,UV}}.
\end{equation}

The large error bars in \(x\) direction are a consequence of the large statistical spread of breakdown voltages in non-aided breakdown events, as shown in figure 6.2.

The data in figure 6.9 can be fitted to a double exponential function of the form

\[ \bar{T}_s = ae^{-be^{-c/OV}}. \]

\begin{equation}
\bar{T}_s = ae^{-be^{-c/OV}}.
\end{equation}

The same same fit can be done for the data obtained at two other frequencies and for breakdown in xenon. The large range of values of the coefficients \(a\), \(b\) and \(c\) that can be used in the fitting procedure makes it inappropriate to ascribe a high degree of certainty to any theory trying to explain these measurements. A good fit can be made with \(c\) ranging from 1 to \(10^{20}\) for the same set of data.
points. Coefficients $a$ and $b$ cannot be chosen in such a wide range of values, their values are typically limited within one or two orders of magnitude.

Still, we would like to comment on the possible origin of the double-exponent dependency on the overvoltage. Equation 6.13 shows that in principle, the statistical time lag is a function of two parameters. Equation 6.3 can be rewritten in the following form, assuming that $\exp \alpha d \gg 1$

$$\frac{1}{P} = \frac{\gamma \exp(\alpha d)}{\gamma \exp(\alpha d) - 1}. \quad (6.16)$$

Electron yield $Y$ is difficult to deduce, since there are numerous theories explaining breakdown in high pressures [9] and we are working in an AC regime, where electron production and loss happens on a larger time scale than in typical pulsed discharge, as shown in chapters 4 and 5. However, if we assume that $Y$ is an exponential function of $\alpha$, as is so often seen in the literature [9],
mean statistical lag becomes proportional to

\[
\bar{T}_s \propto \frac{1}{\exp(\alpha d) \gamma \exp(\alpha d) - 1}
\]

\[
\propto \frac{1}{\gamma \exp(\alpha d) - 1}.
\]

(6.17)

Assuming that \( \gamma \exp(\alpha d) >> 1 \) leaves us with the exponential function in the denominator. Using the form of Townsend’s first ionization coefficient as given in equation 6.1, equation 6.17 can be rewritten as following, for a single value of the electric field

\[
\bar{T}_s \propto \gamma \left( e^{-Apde^{-Bp/E}} \right).
\]

(6.18)

The electric field is presumably a linear function of the applied voltage. Therefore, it is a linear function of the overvoltage, and we can assume \( E = E_0 + E_1 \), where \( E_0 \) is the threshold electric field needed for breakdown and \( E_1 \) is the excess electric field that is present in the experiments. The coefficients \( A \) and \( B \) depend on the gas type.

The reasoning described above can be considered valid for discharges at a constant overvoltage. In our experiments the voltage amplitude slope was positive, and we were working with AC voltage signal. The overvoltage was not constant. However, one should look more closely to the parameter \( \alpha \), which is a steep function of the electric field [7].

Consequently, \( \alpha \) at voltage extremes is a steep function of time in our experiments. Figure 6.10 shows its evolution as a function of time for the voltage amplitude slopes used in our experiments. The calculations for this figure were done with parameters \( A = 12 \text{ cm}^{-1}\text{Torr}^{-1} \) and \( B = 180 \text{ V cm}^{-1}\text{Torr}^{-1} \) [7], for 0.7 bar argon discharge in a homogenous electrode gap of 4 mm. We used a simple expression for the electric field in a homogenous electrode gap, thus underestimating the electric field in the experiments. However, our purpose was only to demonstrate the behaviour of \( \alpha \) with time. Time zero on the x-axis designates the moment where the voltage passed the threshold value needed for breakdown - effectively, the x-axis shows the statistical time lag in the experiments.

The behaviour of \( \alpha \) with time and electric field suggests that a small change in the experimental conditions or timing causes a big change in \( \alpha \), and consequently in the values of \( P \) and \( Y \) in expression 6.13. Therefore, the biggest
contribution is also the one governing the final value of $P$ and $Y$. Consequently, we can say that these parameters and the mean statistical time lag are local functions of the electric field, both in time and in space. We expect that to be the reason why a theory valid only for time independent homogenous electric fields constant in time can also be applied to our case.

6.6 The Cobine-Easton expression

The theory on the structure of time lags by von Laue and Zuber was published in 1925 [132,133] and corrected in 1943 by Cobine and Easton [134]. As we have described in the introductory section, the theory was conceived to describe breakdown in DC voltage conditions. However, it was developed in a way that did not explicitly make use of the DC voltage form. The theory of von Laue and Zuber uses the spread of time lags in the experiments to determine the mean time lag $\sigma$, as given in equation 6.6. According to their theory, probabilities...
$\beta$, $p_1$ and $p_2$ should not be a function of time.

$$\sigma = 1/\beta p_1 p_2.$$  \hspace{1cm} (6.19)

As we were working with AC voltage, these three probabilities were not sufficient to describe our system. One more parameter was also important, and that was the phase in the voltage cycle at which an electron would appear in the electrode gap. The electric fields that governed the breakdown processes in our experiments were the ones at the voltage cycle extremes, as we were working with voltage amplitudes that were not high above the threshold values. Therefore, if an electron would appear in the electrode gap at a moment when the voltage phase was far from an extreme, the chances of this electron to cause an electron avalanche would be very small. This additional parameter, the probability that the electron would appear in the electrode gap at a favourable voltage phase, can be denoted as $p_{AC}$. The aforementioned equation can now be rewritten as following

$$\sigma = 1/\beta p_1 p_2 p_{AC}.$$ \hspace{1cm} (6.20)

This holds only for constant electric fields, or in our case, for the electric fields with amplitudes that are constant in time.

Cobine and Easton have shown that for a voltage that is not constant in time, a slight modification should be made, as in equation 6.7. This modification comes from the fact that for breakdown events in which voltage with slope different than zero is applied, the probabilities $p_1$ and $p_2$ are a function of voltage and therefore a function of time. Our addition $p_{AC}$ is also a function of the voltage amplitude.

The new form of the von Laue - Zuber expression 6.6 is shown in equation 6.7. It contains the parameter $b$ in the exponent, which should have the dimension of $[\text{time}]^{-c}$. However, we do not know how the probabilities $p_1$, $p_2$ and $p_{AC}$ develop with time, and we cannot calculate the mean statistical time lags as a consequence.

From our experiments it can be deduced that the theory of Cobine and Easton can in principle be applied to AC-driven breakdown processes as well as DC. Figure 6.11 shows the log(ln)-log plot of the number of breakdown events with the time lag greater than $t$, as a function of $t$. According to equation 6.7 this plot should give a linear curve for each combination of experimental
Part III.

Figure 6.11: Data on statistical time lags belonging to argon at 0.3 bar and 7 mm electrode gap, at 400 kHz. The data is presented in accordance with the Cobine-Easton relation. Further details can be found in the text.

parameters (frequency, slope, lamp type).

\[ \ln \left( \frac{n_0}{n_t} \right) = bt^c \]
\[ \log(\ln(\frac{n_0}{n_t})) = \log(b) + c \log(t) \] (6.21)

Figure 6.11 shows that the data obtained in the experiments indeed forms sets that can be approximated by linear curves. One should notice that the shapes of the plots greatly depend on the amount of data points that were available, because the ordinate axis basically shows the ratio of the number of the events that fulfill a certain condition and the total number of events. Studying various plots of this type, we have concluded that the linearity indeed improves with the number of data points.

6.7 Conclusions

In this chapter, we have presented the statistical time lag measurements for AC-driven breakdown events, using a slow voltage amplitude slope. The frequency used in the experiments ranged from 100 to 800 kHz and the electrode gap was either 4 or 7 mm.
Statistical time lags varied between roughly 1 and 150 ms, depending on gas type, pressure, electrode gap and voltage amplitude slope. The statistical time lag was greater in xenon than in argon, at higher pressure and smaller electrode gap, which was explained by a smaller number of free electrons available at a given moment in the gas volume.

Statistical time lags were presented as functions of voltage amplitude slope and as a function of overvoltage. A double-exponential function fit was made to the statistical time lags as a function of overvoltage. We suggest that this is the result of specific forms of the mean statistical time lag as a function of Townsend’s first ionization coefficient.

Finally, we have shown that the theory presented in 1943 by Cobine and Easton[134] for breakdown events driven by long square pulses is general enough to show the expected results in the case of AC-driven discharges as well. Further research is needed to examine the extent of validity of this theory in the AC case.
Part IV

Antennas
Introduction

Electrical breakdown in gasses is an extensively researched topic, as it holds interest for academia and the industry alike. The lighting industry has been working on understanding the breakdown processes for decades, the research covering orders of magnitude in pressure for different gasses, voltage forms and various external influences, like UV irradiation. The breakdown process needs to be well understood because it is an essential part of lamp ignition. However, certain properties of the breakdown process, like high speed of development and large jitter associated with breakdown, make the research difficult. The respective relative influences of these properties grow with the pressure of the gas studied. This is why the breakdown process in lamps, especially mid- and high-pressure lamps, is still under investigation [26, 75, 90, 93–97].

The voltage needed for lamp ignition is in general higher than the voltage needed for the steady-state operation. This is true for high intensity discharge (HID) lamps, and it remains a constant challenge because the lowering of the starting voltage of HID lamps could open the door to more efficient or simply cheaper lighting. It has already been reported that the breakdown voltage can be lowered in several ways from the level needed by pulse-ignited lamps - by the use of AC voltage instead of pulses [26] or by using ignition helpers, such as UV irradiation or radioactive electron sources [89, 135]. The two latter forms of ignition aid do not actually allow the breakdown process to run at a lower voltage - they merely reduce the statistical lag caused by the lack of free electrons in the gas gap. The reduction of the statistical lag ensures better ignition reproducibility and therefore better chances that the lamp will start.

The introduction to this part of the thesis has been submitted in a slightly altered form to Journal of Physics D: Applied Physics as a part of the research article Facilitating breakdown in noble gasses at near-atmospheric pressure by using antennas.
during the ignition sequence at a given applied voltage.

The reduction of the breakdown voltage for lamps, not taking into account the reduction of the overvoltage caused by statistical lag, is in its essence a search for the way to either allow the breakdown process to happen in the reduced electric field lower than the minimum value needed now, or to find a way to increase the reduced electric field in the lamp, while keeping the potential on the electrodes constant.

One of the ways to induce breakdown at lower reduced electric field than needed in a pure noble gas is to add a small admixture of a heavier noble gas to the lamp, for example to add a small amount of Xe in a lamp that operates with Ar as a starting gas [95]. At the same reduced electric field, electrons attain a higher mean energy in Ar than in Xe because of the lower electron-atom collision frequency [7]. However, Xe has a lower ionization potential than Ar. What we get as a result is the higher mean electron energy in Ar atmosphere, but we ionize Xe, which has a lower ionization potential. This effectively lowers the reduced electric field needed for the discharge to develop. The same would work for other noble gas combinations, for example small admixtures of Ar in He or Ne. In addition, in noble gas mixtures such as Ar-Ne, the Penning effect has a strong influence on the breakdown voltage as well. This feature is often used to lower the breakdown voltage in HID lamps.

A way of increasing the reduced electric field in the lamp while keeping the potential of the electrodes at the same level and not changing the pressure of the gas is using electrodes with sharp features. However, as soon as a lamp starts burning, sharp features tend to become smoother as a consequence of high electrode temperature. Therefore, sharper electrodes usually do not allow for better ignition properties.

An alternative way of achieving a higher electric field in the plasma region is to use metallic structures on the outer side of the lamp burner. These structures are called “antennas”. The role of an antenna is to bring a finite potential to the vicinity of the electrode system, or later, to the growing discharge. A finite potential close to the electrodes, if chosen properly, could enhance the electric field in the lamp burner by a significant amount with respect to the electric field originally imposed by the electrodes only. In this way, a lower voltage could be used while still maintaining the electric field level needed for breakdown. One of the first commercial lamp in which antennas were used was the high-pressure sodium lamp [5], but the underlying physics that influences
the breakdown process was not described.

Controlling the discharge with the aid of a metal structure that does not take direct part in the discharge formation is not an idea that has been widely researched or documented. The aim of the next two chapters is to study the breakdown process in the presence of antennas, to show how it compares with the breakdown process in the lamp without antennas as described in the chapter 4 and to explain the observed effects.

Chapter 7 deals with the initiation stages of antenna-aided breakdown. Every ignition event can be divided into three stages: inception of the discharge, propagation of the discharge and finally breakdown. The inception can occur only when there is a sufficiently high reduced electric field present. For argon discharges at high pressure, the threshold field was estimated at 3.6 V/cm Torr.

A static electric field model in two and three dimensions was used to simulate the starting conditions in lamps without and with antennas. Several antenna arrangements were tested for best discharge inception conditions. The results have shown that both in lamps with and without antennas the inception has the highest probability to occur at electrode tips or near a junction of the burner wall and the electrode. These two spots are very favourable because of high potential gradients in their vicinity, resulting in electric fields higher than anywhere else in the lamp. Using antennas makes it possible to further enhance the electric field around the two inception-favoured spots and to ignite the same lamp at a lower voltage.

During the inception of the discharge, charge accumulates in the region around the electrode tips, charge density becomes high and the electric field in the lamp is no longer governed by the potential across the electrodes. Furthermore, after the inception phase follows the propagation phase, in which ionized channels form and propagate in the electrode gap. The ionized channel, being conductive, is at a potential close to the potential of the electrode it originated at, almost forming an extension of the electrode. Under these conditions the static electric field model can no longer be used to accurately describe the electric field in the lamp system.

Chapter 8 presents the optical and electrical measurements performed to characterize the AC breakdown process of near-atmospheric pressure noble gas discharges for three different antenna arrangements. We show the differences between the active and passive arrangements and how they influence the break-
down process.
Antennas - Static electric field modelling

7.1 System under consideration

Commercially available software package by Integrated Engineering Software was used to simulate static electric fields in lamps. We used Electro for 2D and Coulomb for 3D simulations. Both programs were used in an electrostatic mode.

The geometry of the lamp used in experiments and described in Chapter 4 was reproduced in the simulations, i.e. a Philips 70 W HID burner commonly used in metal-halide lamps. The burners were made of YAG (Yttrium Aluminium Garnet) to closely resemble the dielectric properties of PCA (Polycrystalline Alumina) used in commercial lamps. The reason YAG was used in our experiments is its transparency, which allowed for optical measurements. The relative dielectric constant of the YAG lamp burner was set to 11.7 in the simulations.

The electrodes in the experiments were made of tungsten, they were rod-shaped and 0.3 mm in radius. Electrode edges were rounded to a 0.02 mm radius to avoid unrealistically high electric fields at the edges. Radius of curvature of the electrode edges in the experiments is not known. However, it has been established that the extremely sharp features on the electrodes typically disappear in lamps due to high electrode temperature during lamp operation.

1Software was made available by dr. Peter A.A.F. Wouters from the Electrical Engineering faculty at Eindhoven University of Technology
Figure 7.1: 2D cylindrically symmetric geometry for use in Electro. The relevant sizes are noted in the picture. This is the Philips 70 W HID metal-halide lamp geometry, with electrode distance of 7 mm.

Figure 7.2: 3D geometry for use in Coulomb. This is the Philips 70 W HID metal-halide lamp geometry, with electrode distance of 7 mm.

Radius of curvature greatly influences the absolute value of the electric field that is calculated in the simulations. However, in this chapter we present results in the form of comparison between the reference case and the antenna-assisted test cases, where the absolute values of the electric fields are not crucial.

A 2D rotationally symmetric geometry was used in Electro, as shown in figure 7.1. The symmetry axis was horizontally placed in line with the lower edge of the electrodes. The electrode gap was held constant at 7 mm. As a general rule, throughout this chapter the electrode shown on the left-hand side is always the active one, charged at 1 kV; the grounded electrode is at the right-hand side. Figure 7.2 shows the full 3D geometry of the same lamp used...
Figure 7.3: Potential distribution for 2D (top) and 3D (bottom) cylindrically symmetric lamp geometry without antennas. Left electrode is charged at 1kV and coloured red, and right is grounded and coloured blue. Colour changes linearly with potential.

The models used a Dirichlet boundary condition for potential on the edges of the computational volumes, more specifically potential on the boundaries was set to zero; in both models we used a computational volume significantly larger than the lamp dimensions in order to avoid the influence of the boundary condition on the calculated potential distribution and electric fields inside the lamp. Figure 7.3 shows the potential distribution in lamps without antennas in 2D and 3D case, to show that the boundary conditions in the model did not visibly influence the calculated potential distribution in the lamps.

The programs used the boundary element method (BEM) to obtain the electric field solutions. Unlike volume-discretization methods, it works by constructing a mesh over the modelled surfaces (or a set of points across one-
Part IV.

Dimensional structures), which makes the calculations more efficient for problems with small surface/volume ratios. However, the storage requirements and computational time grow with the square of the problem size. In 2D modelling we typically used between 800 and 2000 nodes to describe a problem, and in 3D simulations the discretization of the surfaces led to 8000 to 14000 surfaces per problem.

Antennas used in the simulations can be formally divided in at least two different ways - with respect to the symmetry and with respect to the antenna potential.

The division regarding the symmetry separates the antennas into two groups; one where the antennas are cylindrically symmetric with respect to the symmetry axis of the lamp, and one where this is not the case. The first group is simulated in both 2D and 3D, and the results are compared. The second group is simulated in 3D only.

The second division of the antennas is with respect to their potential - floating (passive antennas) and on externally controlled potential (active antennas). The effects these two groups have on the potential distribution in the lamp and the resulting electric fields are of great significance in lamp design.

Figure 7.4: Schematic explanation of electric field presentation. All graphs in this chapter show the electric field as a function of distance \( D \) from the symmetry axis of the lamp. The calculation starts at \( D = 0 \) at the axis and finishes at \( D = 4.5 \) mm, outside the lamp. There are always 4 curves shown in graphs, for 4 points along the active electrode. Names of the points (-3.5 mm, -4.5 mm, -5.5 mm and -6.5 mm) designate distance from the center of the lamp along the anode.
7.2 Reference calculations

This chapter shows the effects of various antenna arrangements on the potential distributions and electric fields in the lamps. Reference calculations were made for a lamp system without antennas. The potential distribution in the 2D case is shown in figure 7.3. The corresponding electric field is presented as a function of distance from the symmetry axis. The principle is shown in figure 7.4. Electric field was calculated along the active electrode, unless stated otherwise. The active electrode is always charged positively in the simulations, so we refer to it as the anode in the rest of the chapter. It should be noted, however, that it does not matter which side of the lamp is at which potential in the reference cases or in arrangements with floating antennas; that is why we always examine electric fields on only one side of the lamp. In reality, conditions are not perfectly symmetric, as there are always grounded surfaces.

![Figure 7.5](image_url)  
**Figure 7.5:** Electric field in the 2D cylindrically symmetric lamp geometry without antennas, as a function of distance $D$ from the symmetry axis of the lamp, as described in figure 7.4.
Figure 7.6: Comparison of electric field in the basic lamp geometry without antennas in 2D and 3D model. The results of 2D calculations are shown on the left, and the 3D model results on the right hand side. Maxima are slightly higher in the 3D model: 11% at the anode tip and 12% at the anode base. Also, the electric field at the anode tip in the 3D case starts at a non-zero value at distance $D = 0$ from the symmetry axis, which points to the fact that the electric field is calculated in front the electrode; in the 2D model this is not the case. The difference is commented on in the text.

Figure 7.5 shows a graph of electric fields as functions of distance from the symmetry axis for the 2D basic lamp geometry. For the first 0.3 mm the electric field is zero, because it is calculated inside the electrode body. At 0.3 mm, the electric field increases rapidly to a value of the order of $10^6$ V/m, which corresponds to the electric field peak at the electrode edge. Afterwards, the electric field strength drops with increasing distance from the lamp symmetry axis. A sharp drop is visible in the electric field values at the position of anode base, at distance $D = 0.6$ mm; this is due to the transition between free air and the dielectric material of the lamp burner wall. The peak of the electric field is highest at the anode tip, as expected, followed by the values near the anode base. Higher values occur in that region because of the proximity of the dielectric to the anode. After the peak, the electric field decreases with increasing distance from the symmetry axis.

Similar results were obtained for the 3D geometry, with slight increase of the peak values of electric field at the anode base (12%) and the anode tip.
(11%). Figure 7.3 shows the potential distribution in the 3D reference case, and Figure 7.6 shows the comparison between the electric fields in 2D and 3D reference case. As shall be seen in all graphs featuring 3D calculations, the electric field for the position at the anode tip appears to be calculated just in front of the anode, and not at the tip as in the 2D model. This can be seen from the electric field values at the distance $D = 0$ mm from the symmetry axis which are greater than zero. They would have been zero if the electric field was calculated inside the metallic electrode material like in the 2D case. However, a small shift into the anode body, at 3.505 mm from the lamp center, gives zero-field values for the volume inside the anode.

During development of geometries for these two models we took great care to ensure that the 3D geometry would be equivalent to the cylindrically symmetric 2D geometry. In fact, the 3D geometry was created by rotating the 2D geometry around the symmetry axis. In that respect, the two geometries are equivalent, but even so, there are differences between the two simulations. These differences can be a result of discretization errors. 3D simulations were done on a coarser grid than used in 2D simulations due to the prolonged calculation times. Another possible reason is a difference in the shape and size of the geometry. In 2D simulations we used cylindrical symmetry, and simulated a cylinder in space. In 3D geometry, the Cartesian system of coordinates was used, thus defining a rectangular box in space. As Dirichlet boundary conditions for potential were used at the boundaries, the difference in coordinate systems could have caused the observed differences in the electric fields. However, we believe that these differences in the calculated electric fields did not pose a real problem in these simulations because the desired result was the influence of antennas on the system, not the absolute values of the electric field.

7.3 Antennas on floating potential

There is a significant difference in antenna design and the effect it has on the breakdown process with respect to the antenna potential. The potential of an active antenna does not depend on its placement with respect to the lamp electrodes. On the other hand, the potential of passive antennas strongly depends on the antenna position in the system, as shown in figure 7.7. A floating ring at an arbitrary position on the outer surface of the lamp burner
has no evident effect on the system, as its potential is the one of the surrounding space; therefore, this ring has no influence on the electric field inside the lamp. For a floating antenna to have a significant influence on the electric field in the system it has to stretch over area of otherwise changing potential, the bigger the potential change the better. The best results are achieved for an antenna stretching across the whole lamp burner, because in this way its potential is an arithmetic average of the potentials across the electrodes. In addition, the antenna positioned in this way reaches close to the two ‘hot spots’ (the base and the tip of the electrode) in the lamp, ensuring a significant potential gradient in their vicinity. However, we could not cover the whole lamp with antennas, because we wanted to obstruct as little light coming out of the lamp as possible, so we chose several more convenient arrangements, such as a spiral, thin uniform coating and a strip. The effects of a grounded spiral, a strip and a set of two active rings are presented in the next section.

7.3.1 Spiral arrangement

Spiral design was approximated as 5 rings at the same floating potential, both in the 2D and the 3D (figure 7.8) case. The potential distribution for a floating spiral antenna in the 2D case is shown in figure 7.9. Antenna potential was the arithmetic average of the potentials at the electrodes, because it was positioned symmetrically across the lamp burner.

There are two special points of interest (the base and the tip of the anode);
the 2D simulations have shown that a metallic spiral at a floating potential enhances the electric field by 100% at the anode base and 18% at the anode tip, thus creating more favorable conditions for the inception of a gas discharge, especially at the anode base. The same conditions in 3D give similar results. There was an electric field increase of 90% at the anode base and 18% at the tip.

7.3.2 Thin uniform coating

Research done by Czichy [75] suggests that thin, conductive coatings on the outside of the lamp burners have a favourable effect on lamp ignition. We tested this type of antenna in the 2D model. The resulting potential distribution is shown in figure 7.10. Using this type of antenna we got a 24% increase
Figure 7.9: Potential distribution of a lamp system with a floating spiral antenna. Left electrode is charged to 1 kV, right is grounded. The antenna is made of tungsten and set on floating potential.

Figure 7.10: Potential distribution of a lamp system with a uniform conductive coating in a 2D simulation. Left electrode is charged to 1 kV, right is grounded. The antenna is made of tungsten and set on floating potential. The coating starts at one electrode base and ends at the other. The places of steep change of potential outside the burner indicates the ending points of the coating.

of electric field at the anode tip and 117% at the anode base. The results are similar to the results obtained when using a spiral; the uniform coating produces only 6% higher electric field at the tip and 9% at the base of the anode.
Figure 7.11: 3D geometry of an antenna arrangement with two metallic rings and a strip connecting them.

Figure 7.12: Potential distribution of a lamp system with a strip antenna with two rings at the sides in a 3D simulation. Left electrode is charged to 1 kV, right is grounded. The antenna is made of tungsten and floating.

7.3.3 Floating strip

The 3D model was used to simulate antennas designs that were not cylindrically symmetric. We implemented an antenna made of two rings and a strip on one side of the lamp - the geometry can be seen in figure 7.11. This design is very similar to the PIA™ arrangement used in Philips HPS lamps. The interest in using a strip as an antenna is in the small area it covers when applied on the lamp surface. Unlike the uniform coating or a spiral, it is confined to one side of the lamp burner and it hardly obstructs the light coming out of the lamp volume. Figure 7.12 shows the potential distribution in the system. This
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arrangement shows 32% increase of the field at the anode tip and 89% increase at the anode base, with respect to the reference 3D case.

In all three passive antennas that we simulated the enhancement of the electric field at the electrode base by far surpassed the enhancement at the electrode tip. This was expected, due to the small distance between the antenna end and the electrode at the electrode base. The lamp geometry was such that it did not allow such small distances between the electrode tip and the antennas; consequently, the difference in the potential gradients between the antenna-aided and non-aided case was much larger at the electrode base.

7.4 Active antennas

One obvious advantage of the active configuration is that the antenna positioning has no bearing on the antenna potential; there is more freedom in antenna design. We chose grounded antennas to test the concept of active systems.

7.4.1 Grounded spiral

The spiral arrangement previously used for passive antenna simulations was employed in the active antenna simulations as well, this time on ground potential. Figure [7.13] shows the resulting potential distribution. It is quite different than the reference case without antennas or with antennas on floating potential; in order to enhance the electric field at the anode, we had to cancel out the electric field at the cathode, thus making it completely inactive during discharge initiation. In return for zero electric field at the cathode, we got a significant increase of the field at the anode. The increase of the electric field in 2D simulations at the anode tip was 127% and 282% at the anode base with respect to the values in the reference case. The potential in the 3D case is also shown in figure [7.13]. The electric field increase with respect to the reference case is 110% at the anode base and 253% at the anode tip in the 3D simulation.

7.4.2 Grounded strip

This is a cylindrically non-symmetric arrangement we were only able to model in a 3D situation. The potential distribution is shown in figure [7.14]. As the
Figure 7.13: Potential distribution of a lamp system with a grounded spiral antenna in a 2D (top) and a 3D (bottom) simulation. Left electrode is charged to 1 kV, right is grounded.

Figure 7.14: Potential distribution of a lamp system with a strip antenna in a 3D simulation. Left electrode is charged to 1 kV, right is grounded. The antenna is made of tungsten and grounded.
antenna is not cylindrically symmetric, the electric field at the cathode tip is not entirely cancelled out, as can be seen in the figure. One more consequence of this asymmetric arrangement is that the potential gradient is also asymmetric with respect to the lamp axis, with the gradient being higher near the antenna strip. This will cause an asymmetric discharge that will grow on the inner surface of the lamp burner on the path closest to the antenna. This antenna arrangement causes a 86% increase of the electric field at the anode tip with respect to the reference case, and a 258% increase at the anode base.

7.4.3 Systems with two rings

Systems with grounded antennas have shown promising results, but at the expense of cancelling out the electric field at the grounded electrode. This would not be considered to be a problem in the case of pulsed ignition, because the discharge is generally starting at the charged electrode - the anode in this case. In AC breakdown both electrodes are the starting points of the discharge, as we have seen in previous chapters; in this case cancelling out the electric field at one electrode could be inefficient. One should keep in mind, though, that here we talk about the inception phase of the discharge development. Having a grounded layer around the lamp could very well help the propagation of the discharge at a later stage.

In order to have a large amplification of the electric field near both electrodes, we designed a two-ring antenna system. Rings were positioned at the sides of the lamp and put on opposite potentials with respect to the closest electrode. Both geometries and the potential distributions can be seen in figure 7.15. The first case was designed for good amplification of the electric field near the electrode base, and the second for field amplification near the electrode tips. In the first case, we got a field amplification of 27% at electrode tips and 235% at electrode base, and in the second case an amplification of 64% at electrode tips and 76% at electrode base with respect to the reference case without antennas.

Even though the reasoning behind this attempt was good (we still got amplification in the right places), the results for individual electrodes are not as good as for the grounded spiral arrangement. With respect to the grounded spiral, the systems featuring the double-active antenna arrangements had 44% and 28% lower electric field at the anode tip for the first and the second arrangement respectively. The electric field was lower by 12% and 54% for the
In this chapter we examined the influence of antennas on electric field in lamps. We used a static electromagnetic model to describe the situation in Philips 70W HID burners as used in metal-halide lamps before discharge initiation, to discover whether the antennas can be used to help lamps ignite and to find the most suitable arrangement for discharge initiation. Electric fields at the anode tip and at the anode base for different antenna arrangements were compared to the reference case of a lamp without antennas. The potential distributions in lamps were also shown to further clarify the manner in which the various antennas affect the lamp systems.

These are the most important findings:

1. The antennas, both passive and active, helped generate higher electric
fields at both points of interest in the lamp - electrode base and electrode tip. In all cases we simulated, there was an increase of relevant electric fields.

2. We found that the passive antennas, in order to have any effect at all, had to be placed over an area of changing potential; best results were obtained for antennas spreading over the whole lamp length.

3. With the passive antennas, we obtained the best results using a uniform coating - increase of the field at the anode base by 117% and by 24% at the tip.

4. The best active antennas gave much higher amplification of the electric field at one electrode, while they completely canceled the electric field at the other electrode. The amplification went up to 282% at the electrode base and 127% at the electrode tip. However, at this point there is no way to predict how the non-existence of the electric field at the other electrode influences the discharge initiation or growth. In the case of AC breakdown, where the discharge in the non-aided situation can start from both electrode tips, the use of active antennas would guarantee the discharge initiation on the active side only.

Table 7.1: Increase of electric field in various antenna arrangements, with respect to the reference cases without antennas, in two- and three-dimensional models.

<table>
<thead>
<tr>
<th></th>
<th>2D simulation</th>
<th>3D simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>anode tip</td>
<td>anode base</td>
</tr>
<tr>
<td>Floating antennas</td>
<td>spiral</td>
<td>uniform coating</td>
</tr>
<tr>
<td></td>
<td>uniform coating</td>
<td>strip</td>
</tr>
<tr>
<td>Active antennas</td>
<td>grounded spiral</td>
<td>grounded strip</td>
</tr>
<tr>
<td>Double-active antennas</td>
<td>two rings - system 1</td>
<td>two rings - system 2</td>
</tr>
</tbody>
</table>
Table 7.1 shows the results for electric field increase for all modelled antennas variations, with respect to the reference cases.

Although very promising results were obtained, it should be noted that this study has been primarily concerned with electric fields in lamps before significant charge accumulation. As we already saw in previous chapters, as soon as the discharge initiates at an electrode tip or at the base, it starts propagating along the highest potential gradient through the gas volume in the lamp. At this point these static simulations are no longer valid because of the high electric field the discharge carries at its tip. From this point on the potential distribution inside the lamp is strongly influenced by the presence of the discharge.

Simulations have confirmed that antennas are able to help discharge initiation in lamps. A dynamic plasma model and experiments are needed to examine the full effect of various antenna arrangements.
Abstract. Electrical breakdown in near-atmospheric pressure noble gasses requires voltages that are quite high, which is undesirable for a large number of possible applications. Metallic structures (antennas) were used on the outer side of the lamp burner to enhance the electric field locally while keeping the same potential difference across the electrodes. Optical and electrical measurements were performed in an argon or xenon atmosphere at 0.3 or 0.7 bar, with 4 or 7 mm between the electrode tips. We used rod-shaped tungsten electrodes of 0.6 mm in diameter. We found that both active and passive antennas facilitate breakdown, and we demonstrated the differences between the two types and their effects on the breakdown process.

This chapter has been submitted to Journal of Physics D: Applied Physics in a slightly altered form.
8.1 Experimental details

8.1.1 Setup

The experiments were done on the setup described in chapter 4. Instead of a vacuum chamber to study discharges, we used HID lamp burners filled with noble gas at near-atmospheric pressure. The geometry was that of a 70W Philips HID burner commonly used in metal-halide lamps, schematically shown in figure 8.1. The burners were made from YAG (Yttrium Aluminium Garnet), which is a transparent material and therefore allows imaging of the breakdown process. It was also chosen for the similarity of its dielectric properties ($\varepsilon_r = 11.7$) to that of PCA (Polycrystalline Alumina) with $\varepsilon_r = 9$, which is a material
normally used in HID lamp burners. The electrodes we used were 0.6 mm in diameter, rod-shaped and made of tungsten. The distance between the electrode tips was set to 4 or 7 mm. The burners were filled with 0.3 or 0.7 bar of noble gas.

The AC voltage was produced by three function generators and subsequently amplified by a combination of a high-frequency amplifier (AR Worldwide 800A3) and a home made transformer coil. The three function generators were coupled together in the following manner: the first function generator (FG1) provided a pulse that triggered both the second and the third function generator (FG2 and FG3) and determined the duration of the final AC signal. The second function generator provided a linear positive ramp, which we used as modulation for FG3. FG3 produced an AC signal with linearly rising amplitude, which is what we used for our experiments.

When establishing the minimum breakdown voltage for lamps with specific antenna arrangement, the slope of the voltage amplitude was varied between 20 and 1280 V/ms. The frequency was varied between 500 kHz and 1 MHz.

For optical imaging we used an AC signal of constant amplitude and frequency, but at an overvoltage - a voltage higher than the minimum breakdown voltage. The reason for this is that the statistical time lag associated with breakdown processes decreases as the overvoltage increases \[9,125\]. Statistical lag is a source of very large jitter during the AC breakdown process, as shown in chapter \[6\]. This jitter would have made the imaging of the breakdown process very difficult if not impossible in a reasonable time frame. Although it was possible to minimize the statistical lag in another way, for example to use UV irradiation \[125,135,136\], we chose not to proceed in this direction, because we were not able to establish with certainty that UV irradiation would only reduce statistical lag of the breakdown process.

For optical measurements we used a Princeton Instruments UNIGEN II filmless GEN III iCCD camera with a \(1024 \times 1024\) pixel array. We took photographs of the visible part of the breakdown process, with gate widths ranging from 100 ns to 1 to 5 voltage cycles (1 cycle = 1.25 \(\mu\)s). There were no multiple photographs of the same discharge taken, due to limitations of our equipment. Every photograph we present in this chapter was taken during a separate breakdown process.

The electrical measurements were done by the means of a high voltage probe and an oscilloscope.
8.1.2 Antenna arrangements

We explored three different antenna arrangements, shown in figure 8.1. Antennas are metallic structures placed on the outer side of the lamp burner wall. For their construction we used metal wire of 0.25 mm diameter, which we wound tightly around the burner to avoid as much as possible the capacitances not accounted for in the calculations. The first antenna arrangement had three windings at each side of the burner wall, connected to each other by a single straight wire. This type of antenna arrangement is also referred to as the antenna strip. The antenna was connected to the grounded electrode, making its potential constant at all times. The second arrangement was a symmetrical passive antenna which differs from the first arrangement only in that it wasn’t connected to an electrode, but was instead at floating potential. The third arrangement was an asymmetrical passive antenna, with 10 windings at the grounded side of the lamp and just one at the active side. Its potential was also floating, but it behaved in a different way than that of the symmetrical antenna. For more explanation, see the Discussion section.

An active antenna arrangement is more difficult to use in practice, because of the difficulties in the production process. Connecting the antenna to one of the lead wires is a complex step in the manufacturing procedure, and it has a low success rate.

We had several lamps of the same type made (we define lamp type as a specific combination of gas, pressure and distance between the electrode tips), in order to avoid any error that might be caused by bad electrodes, impurities or gas leakage. The lamps we used are given in table 8.1. When making breakdown voltage measurements, we took 10 measurements for each lamp and for each data point. We calculated the averages and the standard deviation for each lamp, and then calculated the same for each lamp type. The values and the corresponding standard deviations shown in the graphs represent the average and the deviation for the corresponding lamp type. The optical measurements were done only for argon filled lamps with electrode gap of 7 mm, and for only one lamp of each type.

8.1.3 Overvoltage

The breakdown process consists of several stages - the inception of the discharge, followed by the growth of the discharge, which leads to formation of a
### Table 8.1: Lamp types used in the experiments.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pressure [bar]</th>
<th>Electrode distance [mm]</th>
<th>number of available lamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>0.3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Xe</td>
<td>0.3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

charged channel that bridges the gas gap and ends in the *breakdown moment*. The *breakdown moment* is the moment when the conductance of the channel that previously formed in the gas gap rapidly increases, causing conduction current to start flowing through the channel and a drop of potential difference across the gap. *Breakdown voltage* is the minimum voltage applied across the electrodes at which breakdown is achieved.

The term *overvoltage* is used in this paper quite a few times. In general, this is a voltage that is higher than the minimum voltage needed for breakdown. We could not measure the true minimum breakdown voltage, instead we used as a reference the voltage needed for breakdown at a given frequency and the voltage amplitude slope of 100 V/ms. Overvoltage in this chapter is always determined as the excess voltage amplitude when compared to the breakdown voltage at 100 V/ms amplitude slope; it is almost always given as percentage. Overvoltage was employed only for imaging purposes, to reduce the statistical lag which would have otherwise made our optical measurements impossible in a reasonable time frame.

### 8.2 Time lags in the antenna-aided breakdown processes

Figure 8.2 indirectly shows the effect of the statistical lag on the breakdown process. Breakdown voltage is shown for the symmetrical antenna arrangement at 0.3 bar argon discharge at 4 mm gap and 800 kHz, as a function of voltage amplitude slope. The measurements are compared to the UV-assisted, \(^{85}\)Kr-assisted and non-assisted breakdown processes, all three without antennas. As
Figure 8.2: Breakdown voltage of a 0.3 bar argon discharge at 4 mm between the electrode tips, as a function of the slope of the voltage amplitude. We compare the breakdown process aided by a passive symmetrical antenna with the non-aided, UV-aided and $^{85}$Kr-aided case, all three without an antenna present.

we have already argued in chapter 6, this type of figure indirectly shows the effects of the statistical lag associated with various breakdown processes. We will shortly present the reasoning behind this assumption.

AC breakdown processes have a few general and one specific requirement regarding the free electrons that must be available in the lamp to start an electron avalanche. A free electron has to be present in the gas gap at the moment when the voltage amplitude is high enough so that it can provide a field strength high enough to start an electron avalanche. More specifically, a free electron has to be present when the phase of the sine potential of the active electrode is at $\pm \frac{\pi}{2}$, so that the field strength is at its maximum. Otherwise, the electron will not have enough energy to start an avalanche, because we are working at the lowest voltage at which we can achieve breakdown. This is already a rigorous restriction on the moment when the free electron has to be produced by a cosmic ray or a similar event in the lamp burner.

In addition, the volume of the lamps in question is very small ($3.6 \times 10^{-7} \text{ m}^3$). The probability of producing a free electron in such a small volume at just the right moment is rather limited. This is the source of the large statistical lag and the sensitivity of the statistical lag with respect to the slope of
the voltage. In the same time interval, the voltage rise is higher at the faster voltage amplitude slope. Therefore, in the same voltage interval, there are more free electrons created by external influences when we use a slower slope. More free electrons at the same reduced electric field leads to a higher chance of an electron avalanche \[9\] and therefore to lower statistical lag time.

Figure 8.2 compares the statistical time lags of breakdown processes aided in different ways. The UV-aided measurements show no increase of breakdown voltage across two orders of magnitude in voltage slope. There are two reasons for that. First, the UV source provides between $10^{13}$ and $10^{14}$ 254 nm photons per second in the experimental volume (chapter 4), thus reducing the statistical lag. Second, the formative lag in the breakdown process that could be observed is roughly between 2 and 5 voltage cycles long (1 voltage cycle $= 1.25 \mu$s at 800 kHz) for the given lamp type (chapter 4). The change in voltage amplitude during the discharge formation was thus limited to maximum 10 V at the fastest slope.

**Figure 8.3:** Formative + statistical lag as a function of the applied voltage amplitude for a 0.3 bar argon discharge at 7 mm electrode gap. The three data sets correspond to the symmetrical and asymmetrical passive and grounded antennas. The dashed vertical lines represent the minimum voltage amplitude at which breakdown was achieved at slope of 100 V/ms. The bars represent the spread of the total lag.
In contrast, the rise in voltage slope causes the rise of breakdown voltage in all other test cases, as shown in figure 8.2. The highest values were measured in the non-aided breakdown process, as expected. The 2.5 MBq/l (measured at atmospheric pressure) of $^{85}$Kr in argon provided just a few free electrons in every ignition sequence, thus somewhat reducing the statistical lag. Measurements done for the breakdown aided with a passive symmetrical antenna reveal that the use of an antenna does not minimize the statistical lag, given the fact that the breakdown voltage rises with the increase of the voltage slope. The size of the bars shown in the graph, representing the standard deviation from the mean value, implies that the statistical lag is smaller than for the non-aided and the $^{85}$Kr-aided breakdown process.

The effectiveness of the overvoltage in reducing statistical lag is shown in figure 8.3. This is a plot of combined statistical and formative time lags for breakdown processes with the three different antenna types, as a function of voltage amplitude. The measurements were done for just one lamp filled with argon at 0.3 bar and 7 mm electrode gap. The frequency was the same as during imaging - 800 kHz. Each data point represents the average of 50 measurements, and the bars show the minimum and the maximum time lag measured. Notice that the spread of measurements is asymmetric due to the higher frequency of occurrence of shorter time lags. The figure shows that the increase of voltage amplitude significantly decreases the time lags in the breakdown process. Given the fact that the formative times under these conditions are much shorter than the statistical lag, we can effectively conclude that the use of overvoltage in our experiments significantly shortened the statistical time lag of the breakdown process. This has been shown for non-aided AC breakdown in chapter 6 and will be shown for this experiment as well in subsequent paragraphs.

8.3 Influence of antennas on discharge development

8.3.1 Grounded antenna

We observed the formation of a charged channel in 0.3 and 0.7 bar argon atmosphere for the three antenna types described in the previous section. Figure 8.5 shows the formation of the charged channel in the 0.3 bar argon, at 7 mm electrode gap and with an active (grounded) antenna. The photographs were taken for an arrangement where the antenna strip was positioned on top of the lamp burner, like we have schematically shown in figure 8.1. The grounded
Figure 8.4: Schematic representation of the timing of the breakdown process aided by grounded antenna shown in figure 8.5. Each 100-ns frame is represented as a part of the sine that stands for the potential on the charged electrode. The frames with even numbers are drawn using dashed lines to improve clarity.

The photographs presented in figure 8.5 were taken for an overvoltage of 39%. The visible part of the breakdown process under these circumstances took between 1 and 1.5 voltage cycles. The lowering of the overvoltage to 30% did not increase the duration of the breakdown process. In comparison, the duration of the breakdown process in the same conditions, but without the antenna present, took about 15 voltage cycles, as shown in chapter 4.

We can see that the discharge started as a cloud-like formation around the active electrode, not at its tip, but directly below the place where the antenna structure forms three windings around the side of the lamp burner. With the ground potential so close to the active electrode, this became the place of the maximum electric field instead of the electrode tip. The discharge then proceeded to form a thin channel that grew along the burner surface; the
Figure 8.5: The visible part of the breakdown process aided by an active grounded antenna in 0.3 bar argon at 7 mm gas gap. The camera gate was 100 ns. See figure 8.4 for the timing of each frame.
channel was completed after connecting to the grounded electrode. The same behaviour was observed regardless to the voltage amplitude we employed.

8.3.2 Passive symmetric antenna

![Figure 8.6: Schematic representation of the timing of the breakdown process aided by a symmetrical passive antenna shown in figure 8.7. Each 100-ns frame is represented as a part of the sine that stands for the potential on the charged electrode. The frames with even numbers are drawn using dashed lines to improve clarity.](image)

Figures 8.7 and 8.6 show the breakdown process in 0.3 bar Ar when a passive (floating) symmetric antenna is used on the outer side of the burner wall. There are two important points that distinguish this breakdown process from the one previously shown - first, the breakdown process takes longer when the passive antenna is used, between 2 and 3.5 voltage cycles depending on the voltage amplitude (for 37% and 14% overvoltage, respectively). As a general rule, with the increase of voltage amplitude the formative time becomes shorter. At 0.7 bar, the discharge takes from 1.5 voltage cycles for 121% overvoltage to 12 voltage cycles for 31% overvoltage to form.

The second difference between the discharges at 0.3 and 0.7 bar helped by passive symmetric antennas is that at 0.3 bar, there are two competing discharges that form in the lamp - one along the burner surface below the antenna, and the other in the gas between the electrode tips. When the overvoltage is
Figure 8.7: The visible part of the breakdown process aided by a symmetric passive antenna in 0.3 bar argon at 7 mm gas gap. The camera gate was 100 ns. See figure 8.6 for the timing of each frame.
decreased, the wall discharge disappears and only the one in the gas is formed. This does not hold for the 0.7 bar argon discharges - as far as we have observed, these always form on the burner surface.

8.3.3 Passive asymmetric antenna

Figure 8.8: Schematic representation of the timing of the breakdown process aided by an asymmetrical passive antenna shown in figure 8.9. Each 100-ns frame is represented as a part of the sine that stands for the potential on the charged electrode. The frames with even numbers are drawn using dashed lines to improve clarity.

Figure 8.9 shows the breakdown process when an asymmetrical antenna is employed. As already described in the previous section, the asymmetrical antenna features 10 windings at the grounded side of the lamp (shown on the left side of each photograph) and just one at the active side (the right side of each frame). By using this arrangement, we have tried to come close to the results achieved in the case of an active antenna. For explanation, see the Discussion section.

The asymmetrical arrangement shortened the breakdown process to a value between 2 to 4.5 voltage cycles for the overvoltages between 34% and 9% in 0.3 bar argon. Also, as can be seen in the figures, the discharge looks much more like a discharge formed under the influence of an active antenna - there are no competing discharges, just one single channel growing on the inner surface
Figure 8.9: The visible part of the breakdown process aided by an asymmetric passive antenna in 0.3 bar argon at 7 mm gas gap. The camera gate was 100 ns. See figure 8.8 for the timing of each frame.
Figure 8.10: Breakdown voltage of the 0.3 bar xenon discharge with 7 mm between the electrode tips. We compare the breakdown process aided by the symmetrical passive antenna with the UV-aided and non-aided case.

8.4 Effect on breakdown voltage

Except having an effect on the duration of the breakdown process and the way the charged channel forms in the gas, different antennas also have an influence on the breakdown voltage. We measured the breakdown voltage by applying sine voltage with linearly rising amplitude across the electrodes, changed the slope of the voltage amplitude and the frequency and observed the effects.

Figure 8.10 shows the breakdown voltage for xenon at 0.3 bar and 7 mm electrode gap at a voltage amplitude slope of 100 V/ms, as a function of voltage frequency. A passive symmetrical antenna arrangement was used to aid the breakdown process. The results are compared to the data collected for a non-aided and a UV-aided breakdown process. As we have argued in chapter 4, the UV irradiation employed in experiments that did not feature antennas had just one noteworthy effect: to reduce the statistical time lag of the breakdown process to a very low value. We can see in the figure that for the case of Xe at 0.3 bar, the symmetrical antenna lowers the breakdown voltage to the level of the UV-aided process. This is not the case for all lamp types. The
Figure 8.11: Breakdown voltage as a function of frequency for 0.3 bar argon discharge and 7 mm gas gap. We compare the results obtained for symmetrical and asymmetrical antennas with the data for the active grounded antenna and the non-aided case.

Figure 8.12: Breakdown voltage as a function of frequency for 0.7 bar argon discharge and 7 mm gas gap. We compare the results obtained for symmetrical and asymmetrical antennas with the data for the active grounded antenna and the non-aided case.
breakdown voltage of a 0.3 bar Xe discharge with 4 mm gap and a symmetric passive antenna is 26±10% higher than the breakdown voltage of a UV-aided breakdown process, at 800 kHz. For discharges in argon the breakdown voltage is 11±5%, 14±6%, 13±6% and 6±5% higher when a symmetrical antenna is used than for UV-aided breakdown. The given values correspond to argon at 0.3 bar and a 4 mm gap, 0.3 bar and 7 mm gap, 0.7 bar and 4 mm gap and 0.7 bar and 7 mm gap at 800 kHz, respectively.

Figures 8.11 and 8.12 show the relative influence of different types of antennas, compared to the non-aided case. The measurements were done for the voltage slope at 100 V/ms and at frequencies ranging from 500 kHz to 1 MHz. In both pressures the antennas significantly lowered the breakdown voltage with respect to the non-aided case. In addition, the lamps with active (grounded) antennas required less voltage for a successful breakdown process. The results show that the lamps with symmetrical and asymmetrical passive (floating) antennas required a slightly higher voltage for breakdown than the lamps with the active antennas. Also, in the case of 0.7 bar, the lamps with asymmetrical antennas have a lower breakdown voltage than with the symmetrical arrangement.

8.5 Discussion

In this chapter we characterized the AC breakdown process in argon and xenon in the presence of electric field enhancers (antennas). We experimented in the frequency range between 500 kHz and 1 MHz, using three different antenna types: an antenna on the constant potential (active antenna), and two floating (passive) antennas, one symmetrical and the other asymmetrical. We have shown the effect of the antennas on the breakdown voltage and on the formation of the discharge. The measurements show that, compared to the non-aided breakdown processes, the discharges aided by antennas form on the dielectric surface, rather than in the gas volume. They also have a shorter formation time, and the breakdown process is possible at lower voltages.

The idea behind the usage of antennas was to examine the effects of modifying the electric field in the lamp. We wanted to examine the way in which the breakdown process is influenced in these changed conditions and to explain in which way exactly the active and the passive antennas work. To this end, first we did some static electric field modelling presented in chapter 7.
important to note that a static electric field model can account for the electric field in a lamp system only in the inception phase of the discharge initiation, before the discharge starts propagating in the gas between the electrodes.

The simulations predict that the initial electric field in the lamp was enhanced by 32% at the electrode tips and 89% at the base of the electrodes when a symmetrical passive antenna was used. An active grounded antenna enhanced the initial electric field by 86% and 258% at the charged electrode tip and base, respectively. The electric field at the base was around 32% of the strength of the field at the electrode tip in a reference, non-aided case without an antenna present. Thus, the breakdown process could start at voltages lower than needed for the case without electric field enhancers, because for the same potential difference across the gas gap, we achieved higher electric field at the places in the lamp that are strategically important for discharge initiation.

It is not enough just to ease the inception of the discharge; the electric field strength has to be higher than a certain threshold value in order to maintain its growth. This is why, as a general rule, an arrangement that would just enhance the electric field near the electrodes would not be efficient in lowering the minimum voltage needed for the breakdown process. Instead, we used antennas that stretched across the whole length of the lamp burner. In this way, the proximity of a finite potential to the discharge growing on the inner side of the lamp burner enhanced the electric field at the tip of the growing discharge above the value that could have been achieved without an antenna structure. The overall effect was that a discharge was able to initiate and grow at a voltage lower than the voltage needed without the usage of antennas.

8.5.1 Effect of the dielectric surface

When assessing the influence of antennas on the breakdown process in our experimental geometry, we cannot limit ourselves to the amplification of the reduced electric field in the lamps. The antennas moved the inception spot of the discharge from the electrode tips (chapter 4) to the electrode base, allowing the discharge to grow on the dielectric surface instead of in the gas volume. This was true for all the observed breakdown processes, with exception of 0.3 bar argon with a symmetric passive antenna, where the electric field at the tip was still strong enough to make the electrode tip a strong contender for the inception place of the discharge.
The advantage of a discharge growing on the dielectric surface is that surface discharges in argon grow at higher speed than in the gas volume even without the help of an antenna, as we have previously shown in chapter 2. The higher speed of growth suggested not only an electric field amplification by the dielectric surface, but also that the surface was acting as a pre-charged source. It has already been shown that the preexisting charge on the dielectric surface eases discharge growth [51].

Still, the surface discharges in the experiments on which we report here were of a different type from the ones discussed in chapter 2. The antenna-aided surface discharges can be thought of as guided discharges [28,51]. In guided discharges the presence of the grounded electrode on the far side of the dielectric causes a high electric field amplification. It has recently been conclusively shown [29] that the gas processes are boosted in such a degree that they dominate the surface growth of the discharge. The high electric field amplification can be thought of as an additional effect that allows the discharges to form in shorter times and at lower voltages compared to the non-guided surface discharges.

Taking other effects into account, it has been shown that a discharge forming in the vicinity of the test system can also act as an ignition aid, not by supplying the charged particles, but through light emission [9,137–140]. In particular, it has been shown [141] that surface discharges are efficient sources of UV irradiation and can be used in complex systems like lasers to ensure high enough density of free electrons in the gas gap. Following this argument one can imagine how two competing discharges, like we have seen in our experiment in the case of 0.3 bar argon, can influence each other’s development.

It can be said that the antennas we used not only acted as electric field amplification devices, they also allowed the discharge to grow on the dielectric surface of the burner, additionally easing breakdown. The downside of the discharges growing on the burner surface when the breakdown process was aided by antennas, is that the gap the discharge had to cross was longer than that of a discharge growing in the gas between the electrode tips. This could cause a competition between the surface and volume discharges, as was observed in the case of 0.3 bar argon discharges aided by symmetrical passive antennas.
8.5.2 Active and passive antennas

There is one significant difference between active and passive antennas. The potential of an active antenna is set by physically connecting the antenna to another conductor at a certain potential. This implies that it is possible to fix the potential of an active antenna irrespective of the system we are experimenting on. In our experiments, we connected the active antenna to the grounded electrode, making sure that its potential stays constant. In this way we ensured the proximity of the ground potential to the active electrode and later to the growing discharge, making certain that the electric field at the electrode and at the discharge tip would be significantly amplified with respect to the conditions in a non-aided breakdown process.

The potential of passive antennas is floating, and induced by the electric field set by the electrodes. Our passive antennas featured windings on both sides of the lamp and a piece of wire across the lamp burner, connecting the windings on the sides of the lamp. The schematic representation of the circuit can be seen in figure 8.13. \( V_1 \) and \( V_2 \) represent the potentials at the electrodes, and \( I_A \) and \( V_A \) the current flowing through the antenna and the antenna potential, respectively. The antenna is connected to the potential of the electrodes through capacitances \( C_1 \) and \( C_2 \).

The current flowing through a passive antenna can be calculated using Ohm’s law

\[
(V_1 - V_2) = I_A \left( \frac{1}{i \omega C_1} + \frac{1}{i \omega C_2} \right)
\]

(8.1)

Potential of an antenna can also be expressed in the following ways, according

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{passive_antenna_circuit.png}
\caption{Schematic representation of the electrical circuit using passive antennas.}
\end{figure}


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to the circuit shown in the figure 8.13

\[ V_A = V_1 - \frac{I_A}{i\omega C_1} \quad (8.2) \]

\[ V_2 = V_A - \frac{I_A}{i\omega C_2} \quad (8.3) \]

Combining these equations, we arrive at the expression for the potential of the floating antenna

\[ V_A = V_1 \frac{C_1}{C_1 + C_2} + V_2 \frac{C_2}{C_1 + C_2} \quad (8.4) \]

When we want to apply the formulation shown above to our own experiment, we choose electrode 2 to be the grounded one, thus setting \( V_2 = 0 \). This gives the final expression for the potential of the passive antenna in our experiment

\[ V_A = V_1 \frac{1}{1 + C_2/C_1} \quad (8.5) \]

In the case of a symmetric antenna, the capacitances that couple the antenna potential to that of the electrodes in the lamp are equal \( (C_1 = C_2) \), and the potential of the antenna is equal to one half of the potential of the charged electrode, with respect to ground potential. This is only half of what we achieve with the use of an active grounded antenna. Therefore, the electric field amplification is lower in the case of the symmetric passive antenna, and we need a higher voltage on the active electrode to enable the breakdown process.

One can design a passive antenna with properties such that the antenna potential would be closer to the potential of one electrode than of the other, by adjusting the ratio of capacitances \( C_1 \) and \( C_2 \). In our case, we have made an asymmetrical passive antenna with 10 windings at the grounded side of the lamp, and just one on the side of the active electrode, making \( C_2 = 10C_1 \). According to equation 8.5, the potential of such an antenna is

\[ V_{asymmetric} = 0.09V_1 \quad (8.6) \]

Effectively, the asymmetric passive antenna we used should have ensured similar conditions during the breakdown process as the active grounded antenna. From the measurements of the breakdown voltage shown in figures 8.11 and 8.12, it is clear that this is not true during the whole breakdown process. This is discussed in the next section.
8.5.3 Passive antennas during the breakdown process

The considerations described above are valid for conditions in the lamp before the discharge inception, when the potential distribution in the lamp is given only by the electrode and dielectric geometry and the potential of the electrodes. As soon as the discharge is initiated and a glowing region forms at the base of one of the electrodes, as is indeed the case (see figures 8.7 and 8.9), the ratio of capacitances \( C_1 \) and \( C_2 \) changes. This is an essential difference between active and passive antennas - the potential of an active antenna is not affected by the discharge growing close to the dielectric surface.

Let us consider the capacitances \( C_1 \) and \( C_2 \) in passive antennas. As we have already stated, the antennas were secured at both ends of the lamp by a number of windings. We can approximate the capacitance between an electrode of radius \( a \) and an antenna ring on the outer surface of the lamp burner of radius \( c \) by an expression for a section of a coaxial cable. We have to take into account two capacitances in series - one between the electrode and the inner surface of the lamp burner of inner radius \( b \) (\( C_{gas} \)) and one caused by the lamp burner itself (\( C_{YAG} \)).

\[
\frac{1}{C_{ring}} = \frac{1}{C_{gas}} + \frac{1}{C_{YAG}} \quad (8.7)
\]

\[
C_{gas} = 2\pi \frac{\epsilon_0 l}{\ln(b/a)} \quad (8.8)
\]

\[
C_{YAG} = 2\pi \frac{\epsilon_0 \epsilon_{YAG} l}{\ln(c/b)} \quad (8.9)
\]

\( l \) is the thickness of the wire we used for the construction of the antennas and \( \epsilon_{YAG} \) is the relative dielectric constant of the dielectric lamp material. The resulting capacitance for one antenna winding is

\[
C_{ring} = 2\pi \frac{\epsilon_0 l}{\ln(b/a) + \frac{1}{\epsilon_{YAG}} \ln(c/b)} \quad (8.10)
\]

The capacitance of \( n \) rings is

\[
C_n = nC_{ring} \quad (8.11)
\]

As soon as a diffuse discharge fills the volume between the electrode and the lamp burner wall at the neck of the burner, the part of the capacitance
in equation 8.10 accounting for the effect of the space between the electrode 
surface and the burner surface can be left out. The following expression for 
the capacitance for one antenna winding can be used when a diffuse discharge 
forms around the electrode

\[ C_{\text{ring}} = 2\pi \epsilon_0 \epsilon_{\text{YAG}} l \ln(c/b) \]  

(8.12)

As shown in the Results section, the breakdown process in argon features 
a discharge growing on the inner surface of the lamp burner just below the 
antenna, for both pressures when the asymmetrical passive antenna was used 
and for 0.7 bar with the symmetrical antenna arrangement. This calls for 
another correction to the capacitance ratio between the two sides of the lamp.

The capacitance between the thin charged channel growing on the inside 
surface of the lamp burner and the antenna can be approximated by the parallel 
plate model

\[ C_{\text{strip}} = \epsilon_0 \epsilon_{\text{YAG}} \frac{dl}{c-b} \]  

(8.13)

d is the length of the charged channel that formed below the antenna, l is the 
thickness of the antenna wire, and c − b is the thickness of the dielectric YAG 
lamp burner. In our calculations we have not taken into account the potential 
drop across the charged channel that forms during the breakdown process - we 
have assumed that the potential is the same as at the active electrode. We can 
make this assumption because the channel that forms is indeed ionized, but 
the validity of this premise does not hold for long channels.

The values we used for calculations are listed below. They correspond to 
real dimensions of the electrodes and the YAG burner used in the experiments.

\[
\begin{align*}
a &= 0.3 \text{ mm} \\
b &= 0.4 \text{ mm} \\
c &= 1 \text{ mm} \\
l &= 0.25 \text{ mm} \\
\epsilon_{\text{YAG}} &= 11.7
\end{align*}
\]

The capacitance in the case of one antenna winding at the base of the electrode 
was \(C_{\text{ring}} = 3.8 \times 10^{-2} \text{ pF}\).
Part IV.

Figure 8.14: Influence of the discharge length along the inner burner wall on the ratio of the potential of the passive antennas to that of the charged electrode.

Everything we described above taken into account, we can follow the potential of a passive antenna as the discharge initiates and grows towards the grounded side of the lamp. Results of this consideration are shown in figure 8.14. The graph shows the ratio of the potential of the antenna and the active electrode as a function of the length of the discharge. As our intention was to use the antennas as electric field enhancers, the desired values of $V_A/V_1$ in our experiment would be as small as possible, so that the potential difference between the discharge and the adjacent antenna would be large. It is apparent that the potential of a passive antenna changes drastically over the course of the breakdown process, due to the growth of the discharge.

The initial values for $V_A/V_1$ correspond to the ratios obtained for the time before any discharge growth, given in equation 8.5. The steep increase to less favourable values is caused by the appearance of the diffuse discharge at the base of the charged electrode, that fills the volume between the electrode surface and the burner wall. One can notice a further increase of the ratio $V_A/V_1$, caused by the growth of a thin channel that originates at the base of the charged electrode.

Figure 8.14 shows why the asymmetric passive antennas in our experiments did not perform nearly as well as the active grounded antennas, regarding the enhancement of the electric field in the lamp during both initiation and growth.
of the discharge. It also shows that the passive antennas do not provide a very large amplification of the electric field. Even though the starting conditions appear promising, the emergence of the discharge in the lamp causes the potential of the antenna to be closer to the potential of the active electrode, lowering the effect of the electric field amplification.

Figure 8.14 shows the evolution of the antenna potential for a simple case when the discharge is initiated only at the charged electrode. The reality is a bit more complicated, because it sometimes involves partial discharges on the grounded side of the lamp as well. A diffuse discharge at the base of the grounded electrode, of the same size as the one on the opposite side of the lamp would bring the ratio $V_A/V_1$ close to its initial value, thus creating once again a more favourable environment for the growth of the discharge. This more favourable state would prompt an easier growth of the discharge coming from the active side, but this growth would again increase the ratio $V_A/V_1$. Consequently, in reality we would expect an oscillatory behaviour of the $V_A/V_1$ ratio, causing the speed of growth of the discharge to experience oscillations as well. However, the nature, timing and significance of these oscillations depend to a great extent on the size of the diffuse discharge that would presumably appear at the base of the grounded electrode and its timing, the values of $C_1$ and $C_2$ and the electrode gap. Therefore, there is a whole class of possible outcomes that can potentially result from calculations of the ratio $V_A/V_1$, and most of them have a reasonable chance of happening in real systems.

As a result of the analysis presented above, one can conclude that there are specific aspects of antenna design that have a great influence on antenna performance. We propose three important aspects in passive antenna design, when the desired use of the antenna is to amplify the electric field set by the electrode system:

1. $C_2/C_1$ prior to discharge initiation should be as large as possible
2. $C_2/C_1$ during the discharge development should be as large as possible
3. $C_1$ should be as small as possible and $C_2$ should be as large as possible

In addition, the calculations we made are very sensitive to changes in dimensions. For example, a thicker YAG burner would significantly alter the graph shown in figure 8.14. It is, thus, important to realize that the effectiveness of an antenna can be influenced by the geometry of the experimental system as well.
8.6 Conclusions

We have demonstrated the effects of active and passive antennas on the breakdown process in near-atmospheric pressure argon and xenon. We have shown that the amplification effect of the antennas on the reduced electric field has a twofold role - to increase the reduced electric field at the tip of the discharge, and to make it possible for the discharge to grow along the dielectric surface close to the electrode system. Both results have the same consequence; they ease the discharge initiation and growth and lower the minimum voltage required for breakdown. We have shown the difference between active and passive antennas. Active antennas were found to perform better than the passive ones in both configurations, and we have shown the importance of well-chosen parameters in the passive antenna design.

Having the basic understanding from the electrical point of view about the effects of the antennas on the discharge development, it is now possible to extend the research in various directions. As far as applications in lighting go, this opens a possibility to explore different antenna arrangements, more complex than the ones presented in this chapter, and hopefully more efficient. In the field of guided surface discharges, there are lots of possibilities to further characterize the breakdown process. Experimental results that would ascribe relative importance to various processes present during the growth of guided surface discharges would be a great step in building a more comprehensive theory about surface discharges than what is available today.
Conclusions

9.1 Contents

The aim of the research presented in this thesis is to provide a better understanding of the breakdown phenomena in conditions typical for a mid-pressure high intensity discharge (HID) lamp. The breakdown processes at near atmospheric pressures are known to be erratic, very fast, producing very small amounts of light and, strictly speaking, irreproducible. Consequently, the experimental research into this topic is quite restricted. In order to gain a deeper insight into the problem, we have performed both experiments and simulations.

The topic of breakdown in HID lamps is quite broad, and we decided to focus our efforts on a few particular aspects. We performed our research in argon and xenon, as these are two gases commonly used in lighting industry. However, even though we chose typical HID lamp conditions for the research, throughout this thesis we have tried to present the results of our findings in a broader way that can give a deeper insight into noble gas breakdown irrespective of its final application.

The physics of pulsed breakdown in a gas volume has already been studied quite extensively and reported on in the existing literature. The aspect we have chosen to clarify regarding this topic is the particular role of metastables in the breakdown processes, as the magnitude of the effect of stepwise ionization processes during ignition is not well established.

In some cases pulsed breakdown in HID lamps involves surface discharges,
which is a very broad topic, but not yet well understood. Most of the obtained knowledge is empirical, and even though there are many possible explanations for various observed phenomena, a comprehensive theory on the subject still does not exist. A comparison between volume and surface discharges in the HID-lamp conditions was an aspect of this project designed to provide insight into the role of surfaces during non-aided and antenna-aided breakdown process.

High-frequency AC-driven breakdown processes in noble gasses are an alternative to pulsed breakdown, and a very effective one when it comes to lamp ignition. This is a poorly researched topic, and we needed to establish a basis for possible further research into this subject.

The inquiries to reach the goals set for this project were performed both experimentally and by use of simulations. The experiments were based on iCCD photography and electrical measurements; the data obtained in this way made it possible to compare pulsed surface discharges to the discharges in the gas volume, and to compose a basis for understanding AC-driven breakdown in HID lamps. The effect of metallic structures on the outer side of the lamp burner was examined as well, with application-driven motivation in mind, but also gave results of a fundamental nature. The simulations, which were performed on the modelling platform designed for describing gas discharges, were necessary to gain deeper insight into the fundamentals of the breakdown processes in various conditions, like the effect of the metastables in the breakdown process in near-atmospheric pressure argon. Also, simulations were invaluable for the characterization of AC-driven breakdown and the verification of explanations we have developed by experimental data analysis.

This chapter gives the final set of conclusions on the topics addressed in this thesis. We give a conclusion for every part of the thesis, starting from the comparison between surface and gas volume discharges. The simulations of pulsed breakdown in gas follows, and is succeeded by AC-driven breakdown processes. The influence of antennas is commented on last. The chapter is concluded with a general outlook.

9.2 Surface discharges

The aim of this part of the research was to investigate the influence of dielectric surfaces in the vicinity of an electrode system on the breakdown process. The
Conclusions

Experiments were done in a pin-pin electrode geometry placed in a vacuum vessel with a flat dielectric placed at one side. This gave us the possibility to change the gas pressure in increments that would be complicated to achieve in an enclosed lamp setting. Also, we were able to resolve the influence of the dielectric surface with more certainty than would be possible in a cylindrically symmetric geometry. Argon was used in the experiments, pressure ranging from 0.1 to 1 bar. The reported results were obtained for 25 Hz repetition frequency of experiments. An iCCD camera was used to optically track the discharge. It is important to notice that these were not guided discharges, as no metallic layer was present at the back of the dielectric.

We have demonstrated the tendency of the discharge to propagate on the dielectric surface even in some cases when it was not in contact with the electrode system. The insulating surface had to be relatively close to the electrodes, otherwise the discharge would form only in the gas volume. The reason for this phenomenon is assumed to be the shape of the initial potential distribution which is modified by the presence of a dielectric plate in the vicinity of the electrode system. Also, it has been hypothesized by many researchers that the surfaces can serve as charge source, which may be important during the initiation stage of the breakdown process.

The bulk of the results presented in chapter 2 come from velocity measurements. Two types of velocities were measured - the average velocity of the streamer growth and the velocity as a function of the position in the electrode gap. Higher average velocities were obtained for low pressure discharges due to the higher $E/N$ values at low pressure. Space resolved velocity measurements showed that in our experimental conditions, growth velocity of the discharge is not constant. The main features contributing to this phenomenon are the rising voltage (in contrast to constant voltage often used in experiments) and the geometry of the electrode system.

The same results can probably not be obtained for a pin-plate geometry or pin-gas geometry at these voltages. In order to correctly compare our results with the results obtained in other experimental conditions, one must also carefully compare the used geometry and the voltage. Otherwise, the only result that can be compared is that the discharges forming on the surface do so faster than the ones forming in the gas.

The permittivity properties of the dielectric materials had little influence on the breakdown process. This is understandable, as we were working in a
geometry where the imposed electric field was directed parallel to the insulating surface. In the case of guided discharges, the change of capacitance caused by the dielectric material would be much more pronounced, and one can therefore expect a bigger influence of the permittivity of the material.

Regardless of the particular geometry we used, we have shown that streamer growth on dielectric surfaces is faster than in the gas volume. We have proven this in two ways - firstly by measuring the speed of discharges in gas and on the surface separately, and secondly by measuring them at the same time in the arrangement where the discharges were formed on the surface and in the gas simultaneously. There are several possible explanations for this result. First, the electric field at the streamer tip might be modified by the presence of a piece of insulating material. Also, there is plenty of surface-related explanations, like surface photoionization, photo-detachment of charge from the previously charged surface, field detachment from the previously charged surface or additional energy provided to the electrons by acceleration in the plasma sheath. The photoemission rates were shown [29] to be quite low in comparison to the bulk processes, however, they have the possibility of speeding up the growth by ionizing the gas in front of the high-field region of the streamer tip.

9.3 Pulsed discharges in gas

We have simulated pre-breakdown events in 0.7 bar argon in HID lamp geometries, driven by pulsed voltage. We used a fluid model and a cylindrically symmetric geometry. Five species were included in the calculations - argon atoms, atomic and molecular ions, atomic metastables representing the (4s) metastable states and electrons. A set of reactions was tested and a conclusion was made that the recombination processes do not play a measurable role in pulsed breakdown at near-atmospheric pressure.

The behaviour and dynamics of the breakdown process in gas observed in the experiments were confirmed in the simulations. We have not implemented photoionization in the model; in our simulations the discharge growth is driven only by the high electric field at the streamer tip. The high electric field comes from charge separation in the streamer head, and surpasses the background electric field imposed by the electrode system. The high ionization rates at the streamer tip cause the discharge to sustain its own growth as it spreads in the direction of the applied electric field.
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Considering the short time in which the breakdown occurred in the experiments and the low particle densities, one might expect the stepwise ionization process to be insignificant in pulsed breakdown. However, the atomic metastables are the most numerous species except for the non-excited atom in the breakdown process, and as such their influence was not clear.

By removing the stepwise ionization processes from the chemistry in the simulations and comparing the results to the reference simulation, we have shown that the metastables and the stepwise ionization processes indeed have a measurable influence in the breakdown process. The stepwise ionization consisted of only two reactions, the ionization of metastables by electron impact and the collisional ionization of two metastables, producing one atomic ion, one atom and one electron. The metastable density was not greatly affected, due to the efficient collisional deexcitation of the atomic metastables into the non-excited atomic state. The effect of the lack of stepwise ionization was visible in the charged particle densities. When comparing on-axis (meaning the symmetry axis) values over time, the electron and atomic ion densities at the streamer tip are one order of magnitude larger in the simulation including stepwise ionization.

The most direct proof of the influence of the metastable states and stepwise ionization in the pulsed breakdown process is the decrease of velocity of the discharge growth and the accompanying higher breakdown voltage in the simpler model. The time it took to cross the electrode gap was 31% longer when the stepwise ionization was not included in the model.

In conclusion, metastable states and stepwise ionization processes have an important contribution in near-atmospheric pressure breakdown in argon, in spite of the low density and the high speed of the pulsed process. This finding is important for future breakdown process simulations, especially in conditions where the breakdown process takes a longer time to complete. The results concerning AC-driven breakdown processes are one good example.

9.4 AC-driven breakdown

AC-driven breakdown is a topic not many researchers have studied. We used an HID lamp geometry and AC voltage in the frequency range between 60 kHz and 1 MHz to experimentally determine the main characteristics of this kind of breakdown process and simulations to obtain deeper insight into the param-
eters we could not determine experimentally. The results of the simulations reproduced the experimentally obtained data quite well.

In comparison with pulsed discharges, AC-driven breakdown was possible at lower voltages and it took about three orders of magnitude longer time to complete. Consequently, the simulations done to gain deeper insight into this problem had to include heavy particle transport and recombination processes. As the heavy particles have sufficient time to change position during the discharge development, processes involving heavy-particle dynamics were expected to make a notable contribution in the simulated discharge development. It was shown in chapter [3] that even in fast pulsed breakdown, the stepwise ionization process through atomic metastable states had a measurable influence on the overall breakdown event. In slow AC-driven breakdown, stepwise ionization was expected to have an even larger influence. Similarly, unlike in the pulsed breakdown process where the heavy particles do not have sufficient time to move from the place of their creation [16], the secondary electron emission was expected to play a role in AC-driven breakdown.

We have determined that in this frequency range, gas pressure and electrode gap, the conditions are such that the discharge growth is not limited to one single voltage cycle. At the same time, voltage cycles are sufficiently long to allow electrons produced in one half cycle to drift to the other electrode in the subsequent cycle. The main mechanism of electron loss was indeed drift. Further increase in driving frequency beyond 1 MHz would have caused the transition to the range of diffusion dominated electron loss, as the length of the voltage cycles would become small enough to limit the drift losses.

Experimental and modelling results suggest that the main reason for the observed lowering of the breakdown voltage when AC signal is used instead of a pulsed signal is the secondary electron emission from the electrode surface. The main contributors to this effect were found to be molecular ions, for two reasons. One, their density is much larger compared to the atomic ion density, and they have a greater influence accordingly. Second, unlike metastables, they drift back and forth between the voltage half-cycles, colliding with the electrode and creating new electrons.

One of the effects observed in experiments and confirmed in the model is the lowering of the threshold breakdown voltage with increase in frequency. As electron energy is a function of the applied electric field, one can assume that a lower voltage would result in lower electron energies and therefore lower
electron production rates. As the frequency increases, this bulk production rate lowering is compensated by higher secondary electron emission rates from molecular ion impact at the electrode surface. At higher frequencies there is less time between the two voltage half-cycles. As a result, molecular ions suffer lower losses and produce a greater number of secondary electrons upon their return to electrode surface.

The observed difference between the discharges in argon and xenon can be explained by the difference in the electron-atom elastic collision cross sections in these two gasses. The cross section in xenon is approximately twice as large as in argon in our conditions, as the size of a xenon atom is significantly greater than that of an argon atom. Consequently, electrons in xenon lose energy more efficiently and mean electron energy is lower than in argon. Even though the ionization potential of xenon is lower than that of argon, the lower electron energy makes it more difficult to ionize xenon under the same set of externally imposed conditions.

The experiments on $^{85}$Kr-aided breakdown processes showed that in pure argon, the standard dosage we used had only a limited effect on breakdown characteristics. In geometries of such small volume more radioactive material is needed to have the desired effect of significantly lowering the statistical time lag.

Many experiments were preformed under UV irradiation. Upon detailed analysis of possible effects the UV irradiation might have on our discharges, we have concluded that, in addition to prolonging the formative time lag, its main effect was to reduce the statistical time lag to a negligible value.

The measurements of the statistical time lag in AC-driven discharges revealed that the statistical time lag is a steep function of the voltage amplitude ramp and consequently the overvoltage. The obtained values were between 1 and 150 ms, depending on gas type, pressure, electrode gap and voltage amplitude slope. We found a double-exponential dependency of statistical time lag on overvoltage, for all combinations of parameters.

We have considered established theories on the statistical time lag and found a possible explanation for the observed effects. One should note that those theories were developed mostly for low pressure breakdown, constant overvoltage, and only for breakdown processes driven by voltage signals of monotonous shape. We have shown that in spite of the fact that we were working with AC voltage with rising voltage amplitude, the particular form of the Townsend first
ionization coefficient allowed us to approximate our case with the aforementioned theories. As \( \alpha \) is a steep function of the reduced electric field, probability of breakdown, electron yield and consequently mean statistical time lag depend on conditions local both in space and time.

The theory developed by Cobine and Easton in 1943 for statistical time lag in breakdown processes driven by non-constant monotonous voltage signals was also tested in our configuration. We have found the theory to be valid in our experimental conditions.

\subsection*{9.5 Antennas}

Metallic structures on the outer side of lamp burners (antennas) have long ago been proven to have an effect on the breakdown process. Experimental exploration of breakdown properties was undertaken in the frequency range between 500 kHz and 1 MHz using three different antenna types. The same lamp geometry, pressure, electrode gap and gas types that were used in the AC experiments were used here as well. The effect of antennas on breakdown voltage and discharge formation was demonstrated. The use of antennas was proven to be efficient in lowering of the threshold breakdown voltage.

The lowering of the breakdown voltage is not an effect of reducing the statistical time lag, as in the UV- and \(^{85}\text{Kr}\)-aided breakdown processes. The main reason why breakdown is possible at lower voltage is the fact that instead of having a discharge form in the gas volume, antennas make it possible to have guided surface discharges crossing the electrode gap.

In contrast to the conditions in chapter \( \text{\ref{chapter-2}} \) the electric field imposed by the electrode system in this experiment was not parallel to the insulating surface, as there was a metallic structure placed on the other side of the dielectric. The guided discharges exhibit a feature of much higher amplification of electric field at the streamer tip than the surface discharges described in chapter \( \text{\ref{chapter-2}} \). Such highly amplified electric field causes the bulk reactions in the developing discharge to be by far the biggest contributor to the electron production. Also, guided discharges have been proven to grow at lower imposed voltages than the non-guided ones, and obtain higher growth velocities. This is the reason why breakdown processes in antenna-aided lamps are possible at lower voltages than in the non-aided case.

We have shown that active antennas give better results in lowering the
Conclusions

threshold breakdown voltage than passive antennas. Active antennas are generally speaking on fixed potential, while passive ones are floating. Our choice of potential for active antennas was constant and grounded. The observation that breakdown is possible at lower voltages with active antennas was found in all tested lamp types. The reason for this is not simply that grounded antenna provided a bigger electric field enhancement at the side of the active electrode than passive antenna would. We have tested this hypothesis by using an asymmetric passive antenna, whose starting conditions were almost the same as the ones when using an active antenna.

The reason why an active antenna is more efficient in lowering the threshold breakdown voltage is the fact that its potential does not change over time. As a discharge is initiated at the base of the active electrode, a streamer may develop on the inner burner surface, and the electric field amplification at its tip is more or less constant during the breakdown process.

In contrast, the floating potential of a passive antenna changes as the discharge develops, and over time becomes less and less helpful in guiding the discharge. We have shown that both in case of symmetrical and asymmetrical passive antennas, due to changes in capacitance during the discharge development, the potential of the antenna approaches the potential of the active electrode. This change over time causes less electric field amplification at the streamer tip and consequently less charged particle production and lower growth speed.

9.6 Outlook

A large amount of knowledge has been obtained on the breakdown processes in pure noble gasses at near-atmospheric pressure. We have examined pulsed and AC-driven breakdown in two different gasses and learned about the balance of various processes in both. Both experiments and simulations have been done in order to improve understanding of the underlying processes.

Surface discharges are a topic that needs a lot of additional research. The proximity of the insulating surface to the growing discharge complicates the physics involved because it enables multiple effects to become important in the breakdown process. These effects are not well known and there is no definitive verdict on their relative importance.

The results regarding AC breakdown in this particular frequency range
where the electron losses are still drift-dominated can be used in a wide spectrum of applications. However, there is not much knowledge available on the subject and there is more research necessary. For a start, in order to have a more complete overview, experiments in air are needed, as discharges in air are historically the most well known and also have the widest area of application.

The research presented here makes a good base for further extensions in several directions. Strictly lighting application driven, further research into antenna design could prove useful for further lowering of the threshold breakdown voltage of lamps. Good antenna design has the potential of working equally well in hot restrike conditions as in cold ignition, which was the topic of this thesis. More insight into guided discharges might be needed to make significant advances in this field. The physics of surface discharges also grows in importance if one chooses to study hot restrike of lamps. Preliminary research showed that breakdown processes during hot restrike feature surface discharges, while this is not the case in cold ignition for lamp geometries we investigated.

The wide field of high-voltage engineering is in need of basic understanding of the processes involved in growth of surface discharges. The scale of the problem is slightly larger than what was presented here, both regarding physical dimensions and the voltage used. However, the same physics still applies, and the theory on surface discharges is far from being complete. This particular industrial branch would profit from experiments revealing the nature of interaction of streamers and dielectric surfaces. Extending the problem to AC voltage sources might also be of interest for high-voltage engineers, as the surface discharges driven by AC voltage have also been known to cause damage. We have made steps in this direction when considering the antenna-aided AC breakdown. The possibilities to build on the data we obtained are numerous and possibly also interesting in additional industrial application areas, such as surface and gas cleaning. The efficiency of AC-driven surface discharges for these applications still has to be determined.
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Journals

*The effect of an antenna on the breakdown process in an HID lamp*

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*Statistical time lags in AC discharges*

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Speed of streamers in argon over a flat surface of a dielectric

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AC ignition of noble gas discharges

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Influence of a dielectric on discharge ignition

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Electrical breakdown in the proximity of a dielectric
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