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# Physics of Electrical Discharge Transitions in Air

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*To the Lord*

*&*

*To the uncertainty and imperfection of life*

# Abstract

Electrical discharges with a variety of different forms (streamers, glow corona, leaders, etc.) broadly exist in nature and in industrial applications. Under certain conditions, one electrical discharge can be transformed into another form. This thesis is aimed to develop and use numerical simulation models in order to provide a better physical understanding of two of such transitions, namely the glow-to-streamer and the streamer-to-leader transitions in air.

In the first part, the thesis includes the two-dimensional simulation of the glow-to-streamer transition under a fast changing background electric field. The simulation is performed with a fluid model taking into account electrons. An efficient semi-Lagrangian algorithm is proposed to solve the convection-dominated continuity equations present in the model. The condition required for the glow-to-streamer transition is evaluated and discussed. In order to enable such simulations for configurations with large interelectrode gaps and long simulation times, an efficient simplified model for glow corona discharges and their transition into streamers is also proposed.

The second part of the thesis is dedicated to investigate the dynamics of the streamer-to-leader transition in long air gaps at atmospheric pressure. The transition is studied with a one-dimensional thermo-hydrodynamic model and a detailed kinetic scheme for $N_2/O_2/H_2O$ mixtures. In order to evaluate the effect of humidity, the kinetic scheme includes the most important reactions with the $H_2O$ molecule and its derivatives. The analysis includes the simulation of the corresponding streamer bursts, dark periods and aborted leaders that may occur prior to the inception of a stable leader. The comparison between the proposed model and the widely-used model of Gallimberti is also presented.

**Keywords**: electrical discharges, transition, streamers, glow corona, leader discharges.

# Sammanfattning

Elektriska urladdningar av olika former (streamers (*från engelska*), glöd-korona, ledare, etc.) förekommer i stor utsträckning i naturen och i industriella applikationer. Under vissa förhållanden kan en elektrisk urladdning omvandlas till en annan form av elektrisk urladdning. Denna avhandling syftar till att utveckla och använda numeriska simuleringsmodeller för att ge en bättre fysikalisk förståelse av två sådana övergångar, nämligen glöd-till-streamer- och streamer-till-ledar-övergångar, i luft.

I den första delen, avhandlas en tvådimensionell simulering av glöd-till-streamer-övergången med ett hastigt föränderligt elektriskt fält i bakgrunden. Simuleringen utförs med en flödesmodell som tar hänsyn till elektronerna. En effektiv semi-Lagrangesk algoritm föreslås för att lösa de konvektionsdominerade kontinuitetsekvationerna i modellen. Vidare utvärderas och diskuteras förutsättningarna för glöd-till-streamer-övergången. För att möjliggöra sådana simuleringar i konfigurationer med stora elektrodavstånd och långa simuleringstider, föreslås också en effektiv och förenklad modell för glöd-korona-urladdningar samt deras övergång till streamers.

Den andra delen av avhandlingen är tillägnad att undersöka dynamiken i streamer-till-ledar-övergångar över långa avstånd i luft, under atmosfäriskt tryck. Övergången studeras med en endimensionell termohydrodynamisk modell och en detaljerad kinetisk modell för blandningar av $N_2/O_2/H_2O$. För att utvärdera effekten av luftfuktighet, innefattar den kinetiska modellen de viktigaste reaktionerna med $H_2O$-molekylen och dess derivat. Analysen innefattar simuleringen av motsvarande streamer-kedjor, mörka perioder och avbrutna ledare som kan förekomma före starten av en stabil ledare. En jämförelse mellan den föreslagna modellen och den allmänt använda modellen av Gallimberti presenteras också.

**Nyckelord**: elektriska urladdningar, övergång, streamers, glöd-korona, ledarurladdningar.

# Acknowledgements

First and foremost, my deepest acknowledgement goes to my supervisor and one of my best friends, Marley Becerra. I feel deeply honoured to have such a great scientist as my mentor, not only regarding academic matters but also in life.

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I enjoyed a lot the life in Stockholm and at KTH Royal Institute of Technology. As a prestigious technical university, KTH provided valuable insight and invaluable assistance from international, experienced and well-recognized scientists and engineers. The adequate academic resources, harmonious interpersonal relationships, flexible schedules and the beautiful environment…all these elements make me feel relaxed, confident and energetic when pursuing my Ph.D. studies.

There are a lot of people I would like to acknowledge, my colleagues at the department of electromagnetic engineering of KTH, my friends in Stockholm, my sisters and brothers in the Immanuel Church in Stockholm, and my family. Without their support, companionship and encouragement, this thesis would have been impossible to finish. I will not list their names here, but I will keep them in my mind.

The scenes and memories in the last four years are always vivid. I remember when I came to Sweden and posted some pictures on the Internet with text '*Happy Ph.D. life begins*'. The post caused a heated discussion and was forwarded by thousands of people since most of them think the word '*happy'* contradicts the word '*Ph.D. life*'. Yes, I have to admit that pursuing Ph.D is not easy. However, I really enjoy it and I feel so lucky and honoured. For me, it is like a journey abroad, meeting different people, doing different things and seeing different sceneries.

Happy Ph.D. life ends here, but it lasts forever in my heart.

*Lipeng Liu*

*Stockholm, May 2017*

# List of Publications

This thesis is based on the following papers, which will be referred to in the text by their roman numerals:

I. **L. Liu**, M. Becerra, "An efficient semi-Lagrangian algorithm for simulation of corona discharges: the position-state separation method," *IEEE Transactions on Plasma Science*, volume 44, issue 11 (10 pp), 2016. (doi: 10.1109/TPS.2016.2609504)

II. **L. Liu**, M. Becerra, "Application of the position-state separation method to simulate streamer discharges in arbitrary geometries," *IEEE Transactions on Plasma Science*, volume 45, issue 4 (9 pp), 2017. (doi: 10.1109/TPS.2017.2669330)

III. **L. Liu**, M. Becerra, "On the transition from stable positive glow corona to streamers," *Journal of Physics D: Applied Physics*, volume 49, issue 22 (13pp), 2016. (doi: 10.1088/0022-3727/49/22/225202)

Conference paper version presented at the 20th International Conference on Gas Discharges and their Applications, Orleans, France, 2014.

IV. **L. Liu**, M. Becerra, "An efficient model to simulate stable glow corona discharges and their transition into streamers," *Journal of Physics D: Applied Physics*, volume 50, issue 10 (12pp), 2017. (doi: 10.1088/1361-6463/aa5a34)

V. **L. Liu**, M. Becerra, "Gas heating dynamics during leader inception in long air gaps at atmospheric pressure," (23pp), submitted to *Journal of Physics D: Applied Physics*, 2017.

Conference paper version presented at the 21st International Conference on Gas Discharges and their Applications, Nagoya, Japan, 2016.

VI. **L. Liu**, M. Becerra, "Two-dimensional simulation on the glow to streamer transition from horizontal conductors," presented at the 32nd International Conference on Lightning Protection, Shanghai, China, 2014. (doi: 10.1109/ICLP.2014.6973247)

VII. **L. Liu**, M. Becerra, "Two-dimensional simulation on the glow to streamer transition from lightning rods," presented at XIII International Symposium on Lightning Protection, Balneário Camboriú, Brazil, 2015. (doi: 10.1109/SIPDA.2015.7339289)

The above papers are reprinted in the appendix with kind permission from the publishers: © IEEE 2014, 2015, 2016, 2017 and © IOP Institute of Physics 2016, 2017.

Other contributions of the author, not included in the thesis

VIII. **L. Liu**, M. Becerra, "A parallel projection method for the solution of incompressible Navier-Stokes equations based on position-state separation method," presented at the 27th International Conference on Parallel Computational Fluid Dynamics, Montreal, Canada, 2015.

# Contents

# 1 Introduction

"*The eternal mystery of the world is its comprehensibility.*"

"*If you can't explain it simply, you don't understand it well enough.*"

"*Imagination is more important than knowledge.*"

Albert Einstein

Electrical discharges are usually produced under strong electrical fields where electron multiplication occurs. They can be localized in high electric field regions such as in the case of corona discharges, or can propagate in the medium as in lightning discharges. This thesis will not deal with electrical discharges in solids or liquids, but will focus on the most common gaseous medium: air. Generally, an electrical discharge in air can be viewed as plasma, however, not *vise versa* (e.g. a flame is plasma but not an electrical discharge).

The scientific research on electrical discharges in air started several hundreds of years ago. For example, the research of lightning is considered to have started with the American scientist Benjamin Franklin in 1746 when he conducted experiments on electricity [1]. His famous kite experiment in 1752 led him to define the sign of electrical charge and he concluded that the lower part of a thundercloud is usually negatively-charged [1]. The industrial applications of electrical discharges also date back to the $18^{th}$ century. In 1770, English physicist Joseph Priestley discovered the erosive effect of electrical discharges, which led to the invention of electrical discharge machining technology [2]. Later in 1785, the Dutch chemist Martinus van Marum noticed that ozone can be produced by electrical sparking in oxygen [3]. Research on electrical discharges is not only an old, but also a prosperous subject with some discharge phenomena such as transient luminous events discovered only a few decades ago [4-6] and with emerging applications in industry [7-9]. One type of electrical discharge can be transformed into another form under certain conditions. The condition required for such a transition to take place is thus of great interest to investigate, not only from the theoretical point of view, but also from the perspective of engineering applications.

In the first part of this chapter (section 1.1-1.3), background regarding different forms of electrical discharges in air and their transitions are introduced. The second part (section 1.4) is devoted to briefly describe the motivation and the structure of this thesis.

## 1.1 Examples of electrical discharge phenomena in air

Electrical discharges in air widely exist in nature and industry. The most famous and common discharge phenomenon in nature is lightning, which is a rapid electrostatic discharge that usually happens during thunderstorms. Due to the electrification of thunderclouds, electrical discharges in nature occurs in several different ways, for example in cloud-to-cloud and cloud-to-ground flashes and in upper-atmospheric lightning such as blue jets, gigantic jets and sprites [6]. Figure 1.1 illustrates the different phenomena associated to lightning at different altitude in the atmosphere.

On earth, lightning frequently strikes 40-50 times every second, of which about 25% correspond to cloud-to-ground lightning flashes [10]. Due to the flow of very large currents (several tens of kA) within a short time, lightning can injure people and damage or disturb directly or indirectly structures and their internal equipment [11]. Lightning is the second leading cause of weather-related death in the world [12]. In particular, lightning is a threat to tall grounded structures such as buildings, ultra-high voltage (UHV) power transmission lines and wind turbines.

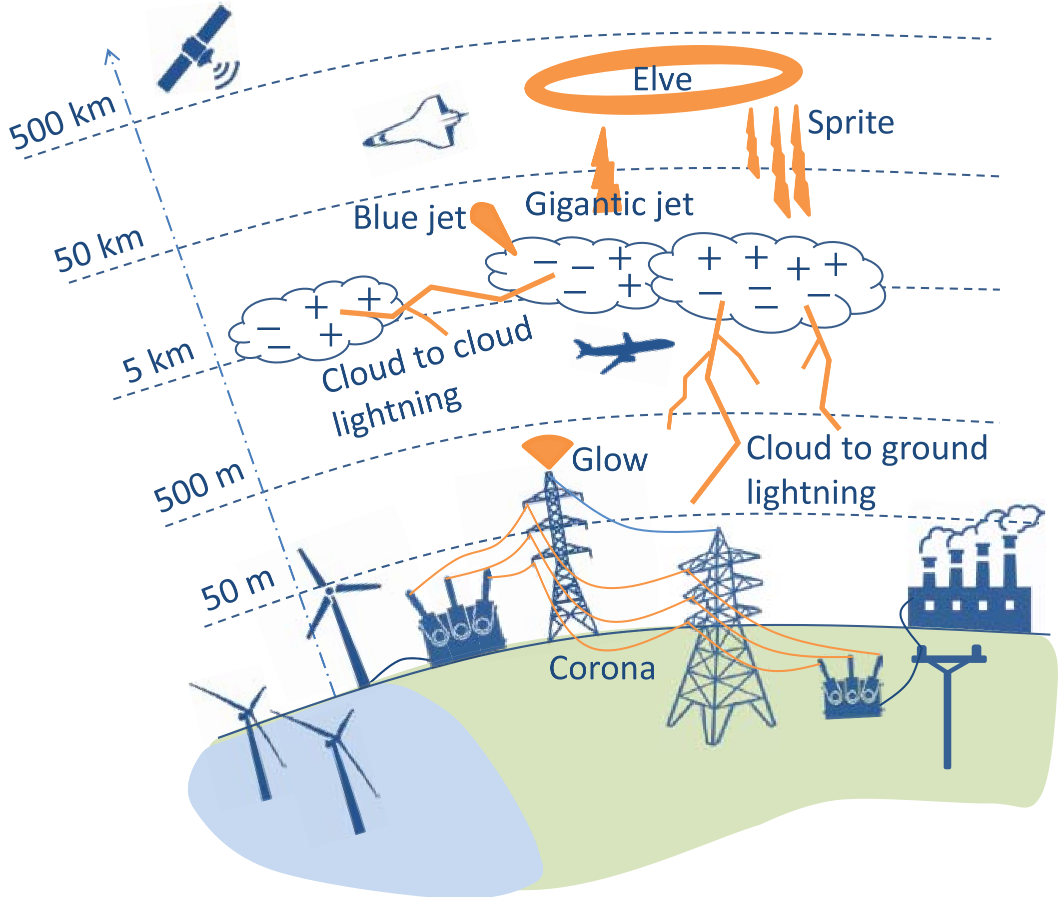


Figure 1.1 Conceptual sketch of different kinds of discharge phenomena in the atmosphere. Part of the illustration of electrical discharges in the upper atmosphere is adapted from [6]. An example of UHV power grid systems is shown to illustrate discharges commonly present in industrial applications.

During thunderstorms, glow corona can be produced by towers (as illustrated in figure 1.1), lightning rods, masts, chimneys and wind turbines due to the high electric field induced at the tip of these structures. The corona discharge usually emits a faint glow of light with blue or violet colour that can only be seen in the dark. The glow generated from masts was noticed by sailors several hundreds of years before Benjamin Franklin's electrical experiments. The sailors viewed glow corona as a sign from the patron saint of the sailors, St. Elmo and thus named it as *St. Elmo's fire* [11].

The most common electrical discharges in industry are corona discharges. For example, corona widely exists in high-voltage power transmission lines, as illustrated in figure 1.1. These corona discharges are undesirable since they can cause power energy loss, audible noise and insulation damage [13]. On the contrary, corona discharges are also very useful in technological areas such as the ozone production, surface treatment, and pollution control [7]. In industry, electric arcs are another type of electrical discharges that play an important role. Although electric arcs are undesirable in electrical devices such as switches and circuit breakers, they are widely used in welding, lighting, electrical discharge machining [9], etc.

## 1.2 Typical forms of electrical discharges in air

### 1.2.1 Fundamental processes in electrical discharges

As illustrated in figure 1.1, there are different kinds of electrical discharges in the upper atmosphere (developing under low air density) such as sprites, blue jets, gigantic jets, and elves. These phenomena have different properties compared to electrical discharges under atmospheric conditions. For example, sprites consist of thousands of growing channels with diameters of the order of tens to hundreds of meters [14]. On the other hand, they also share close similarities to discharges produced in the laboratory [15, 16]. For instance, large-scale sprites are physically similar to small-scale streamer dischargers in air at atmospheric pressure [17, 18], blue jets emit a fan of streamers similar to the streamer corona zone in front of laboratory leaders [19], and gigantic jets have similar characteristics as leader discharges in laboratory [20]. This thesis will not discuss the upper-atmosphere discharges and their transitions in details, but will focus on the traditional discharges at atmospheric pressure.

Electrical discharges are plasmas consisting of six types of species: free electrons, atoms and molecules, excited atoms and molecules, positive ions, negative ions, and photons [21]. Among these species, free electrons are the most important specie which dominates the discharge process due to their special features. For example, electrons drift with velocities two orders of magnitude faster than ions under the same electric field.

Figure 1.2 illustrates some typical fundamental processes where electrons are involved.

For example, electrons can be produced by impact-ionization, photo-ionization, and detachment processes while they are lost through recombination with positive ions and attachment with neutral molecules to form negative ions. As shown in figure 1.2, electrons are usually bound in different energy levels. Electrons in low energy levels can 'jump' into high energy levels (through excitation), or even become free electrons by collisions or by electromagnetic radiation. Electrons in high energy levels can also 'return' to low energy levels and emit photons (through quenching). For a detailed introduction of these processes as well as the general kinetic theory of electrical discharges, the reader is referred to classic books in the subject such as [22-25].

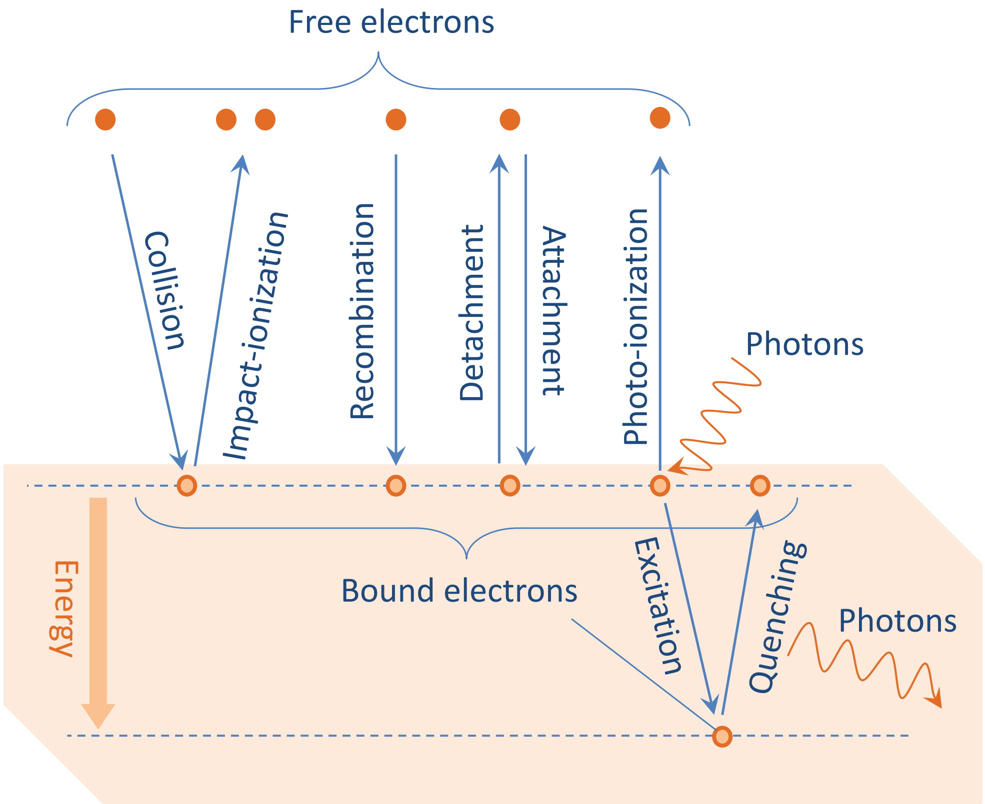


Figure 1.2 Sketch of typical fundamental processes of electrons in air.

## 1.2.2 Development of typical electrical discharges

The research of electrical discharges has a long history. After Benjamin Franklin, an important step in the research of gaseous discharges was taken by English chemist and physicist Sir William Crookes, who invented vacuum tubes in 1875 [26]. Shortly after, British physicist John Sealy Townsend proposed the famous theory of Townsend discharges around 1900 [27] to explain the breakdown characteristics in short gaps at low pressures. However, there are several experimental observations in longer gaps at high pressure which cannot be explained by Townsend theory. For instance, experimental measurements in cloud chambers show that electron avalanches propagate with a velocity much larger than the electron velocity under the applied electric field. In addition, it was observed that the discharge can propagate not only towards the anode but also towards the cathode. These observations led scientists to define a different type of process: the streamer discharge. The theory describing streamers was proposed around 1940s, independently by L. B. Loeb and J. M. Meek [28, 29] and H. Raether [30].

Including streamers, all electrical discharges require free electrons to get started. In air, few free electrons $n_0$ are produced by background radiation such as terrestrial radiation and cosmic rays [15, 31], through the reaction

$$\mathrm{M} \xrightarrow{\text{radiation}} \mathrm{M}^+ + e \qquad (1.1)$$

where M denotes neutral molecules such as $\mathrm{N_2}$ and $\mathrm{O_2}$. The maximum electron density produced by background radiation at ground can be up to $10^4\ \mathrm{cm^{-3}}$ [31].

Under high electric fields, the number of free electrons $n_e$ can increase exponentially with time $t$ once ionization frequency $v_i$ exceeds attachment frequency $v_a$ expressed as

$$n_e(t) = n_0 \exp[(v_i - v_a)t] \qquad (1.2)$$

In dry air, $v_i > v_a$ occurs when the reduced electric field $E/N$ is larger than 120 Td (1 Td = $10^{17}$ V $\mathrm{cm^2}$), where $E$ is the electric field and $N$ the number density of air [32]. Once the electric field is above the threshold when $v_i = v_a$, electron avalanches are produced. At atmospheric pressure (with $N = 2.5 \times 10^{19}\ \mathrm{cm^{-3}}$), the electric field threshold $E$ is around 30 kV $\mathrm{cm^{-1}}$.

Figure 1.3 (a) shows a cloud chamber photograph of a single electron avalanche. If the net charge in the head of the avalanche is not sufficient to distort the electric field, the avalanche moves with the electron drift velocity [7]. If secondary electrons are produced during the lifetime of the avalanche, for example by photoionization as sketched in figure 1.3 (b), the avalanche can grow quickly into a streamer. There is a minimum radius of the avalanche $r_s$ which is required for the streamer transition [33, 34]. At atmospheric pressure, $r_s \approx 0.2$ mm [33]. Figure 1.3 (c) is a cloud chamber picture showing the transition from avalanches into a streamer.

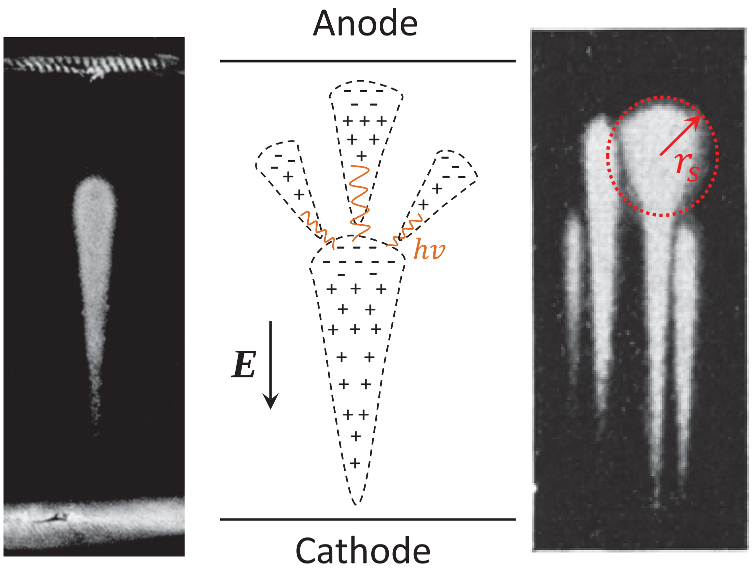


Figure 1.3 (a) Typical cloud chamber photograph of a single electron avalanche, adapted from [30]; (b) Conceptual sketch of the electron avalanche development under a uniform electric field; and (c) Cloud chamber photograph showing the transition from avalanches into streamers where the initial radius of the streamer $r_s$ is marked, adapted from [35].

The most common setup in the laboratory to produce electrical discharges is the point-plate configuration, as illustrated in figure 1.4. This figure also illustrates different basic forms of electrical discharges at atmospheric pressure. As the voltage applied to the electrode increases, streamers can be firstly produced from electron avalanches as described in the previous subsection. These streamers are generally known as pre-onset streamers [26]. Depending on the applied voltage and gap distance, different forms of electrical discharges can be produced. In short gaps under high voltage, streamers can reach the opposite electrode leading to streamer breakdown, which usually develops into an electric arc. Electric arcs can be sustained if the applied voltage is maintained. If the produced streamers cannot bridge the gap, corona discharges will be formed. Under electric fields slowly changing in time (e.g. under DC voltages), the discharge is self-sustained in a limited region around the electrode. Depending on the electrode and applied voltage, corona discharges usually have two typical modes, namely streamers with filamentary structures and homogeneous glow [36, 37]. In long air gaps (> 1 m), the current of a large number of branching filaments in a streamer can contract into distinct stems. Leader discharges can be incepted if the stem of a streamer reaches a temperature of about 2000 K [23, 38, 39]. If the electrostatic conditions are sufficient, the leader channel acts as an elongation of the electrode since the electric field along the channel is rather low. Then, the channel can propagate into the gap by thermalizing air through the current collected from the streamer corona produced at its tip. The corona region ahead of the leader tip is also known as the streamer zone. Figure 1.5 shows a typical streak image of positive leader propagation in a rod-plane gap in air, where the leader tip and the streamer zone can be clearly seen. Leader discharges are the most important breakdown mechanism in long air gaps (> 1m) [24]. Once the streamer at the tip of a leader channel reaches the opposite electrode, leader breakdown occurs. In this case, an electric arc can also be formed if the applied voltage is maintained.

Streamers and glow corona are non-thermal plasmas where the gas temperature is usually low [7]. For this reason, streamers and glows are also classified as cold plasmas. However, the electronic temperature of cold plasmas is much larger than the gas temperature (translational temperature). Leader discharges and electric arcs are instead thermal plasmas which much higher gas temperature (> 2000 K).

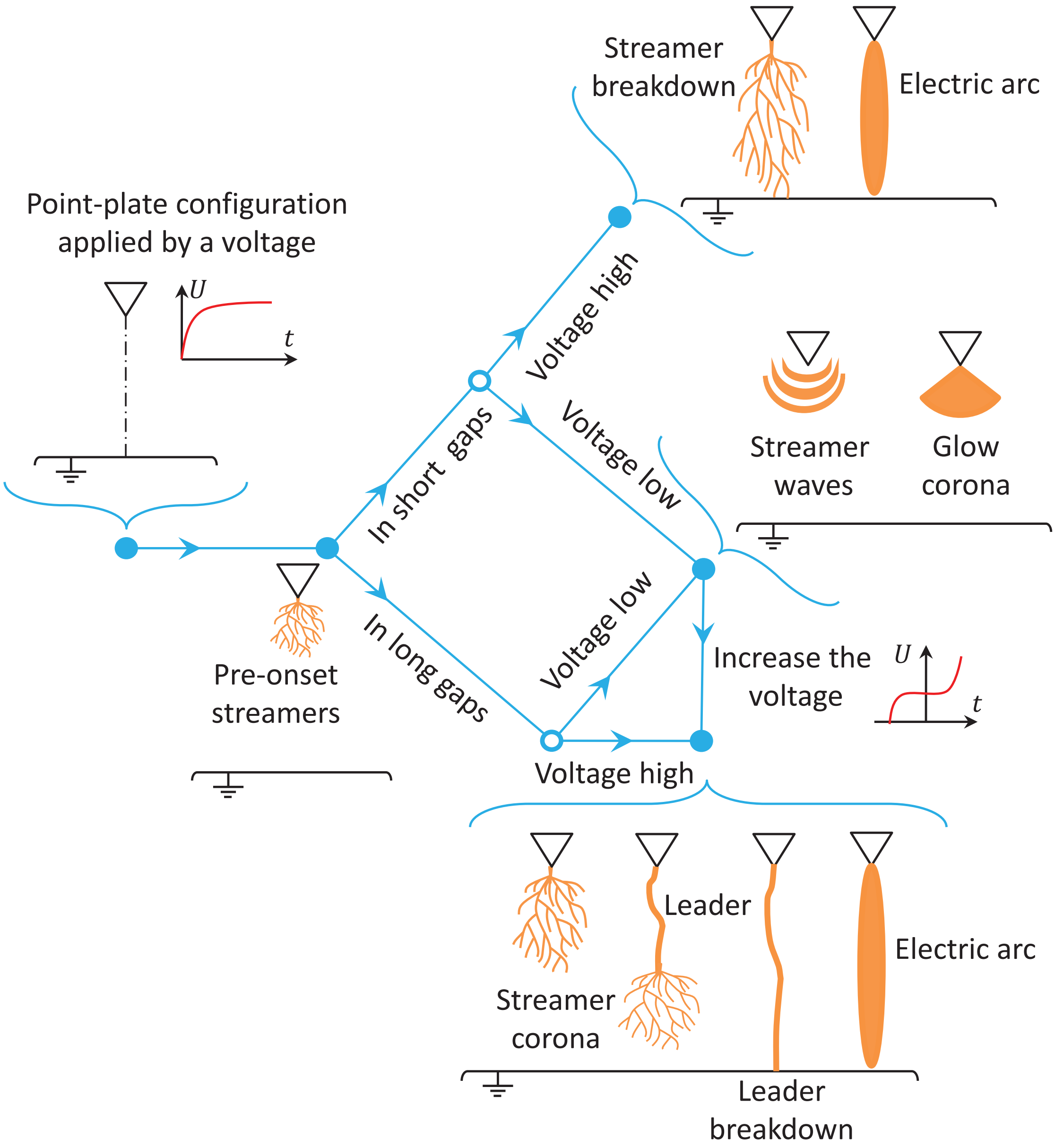


Figure 1.4 Sketch of typical electrical discharges in non-uniform fields at atmospheric pressure.

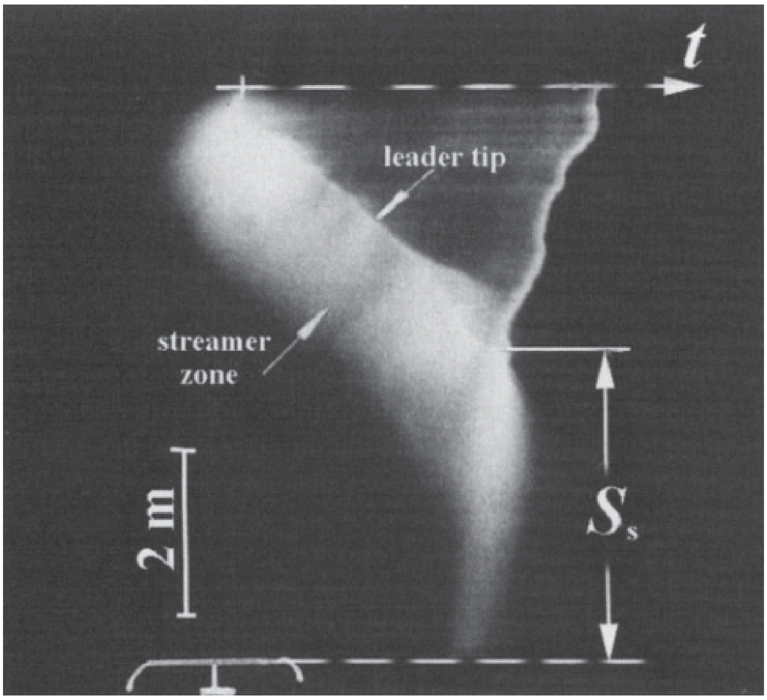


Figure 1.5 Streak photograph of the propagation of a positive leader discharge in a rod-plane gap in air. Photograph reprinted from [40] with permission.

## 1.3 Typical electrical discharge transitions in air

Figure 1.6 illustrates typical electrical discharge transitions at atmospheric pressure marked as T1-T5. The short description of these transitions is given as

- *Avalanche-to-streamer transition* T1: defines the formation of streamers as introduced in section 1.2.2. The electron density of the avalanche has to reach about $10^{14}\mathrm{cm}^{-3}$ at atmospheric pressure [33] for this transition to occur.
- *Streamer-to-glow transition* T2: describes the formation of glow corona from pre-onset streamers, for example under a DC voltages as in [41]. Since the applied voltage is not sufficient to cause a streamer breakdown or a leader breakdown in the gap, glow corona discharges are restricted around the surface of the electrodes and are uniformly distributed, as shown in figure 1.4.
- *Glow-to-streamer transition* T3: glow corona discharges can be transformed to other modes such as streamer bursts and breakdown streamers depending on the voltage amplitude and the geometry [36]. In this thesis, however, the glow-to-streamer transition refers to the transition from glow corona to streamers under fast rising applied voltages, as shown in figure 1.4.
- *Streamer-to-leader transition* T4: is defined by the formation of leader discharges from streamer corona. The streamer-to-leader transition takes place not only before the inception of a stable leader, but also during the leader

propagation. In this thesis, more attention is focused on the first stage, i.e., the leader inception.

- *Breakdown-to-arc transition* T5: describes the transition of any breakdown process into an arc discharge. Electric arcs in air at atmospheric pressure usually have much higher current and temperature (> 5000 K) than for leader channels.

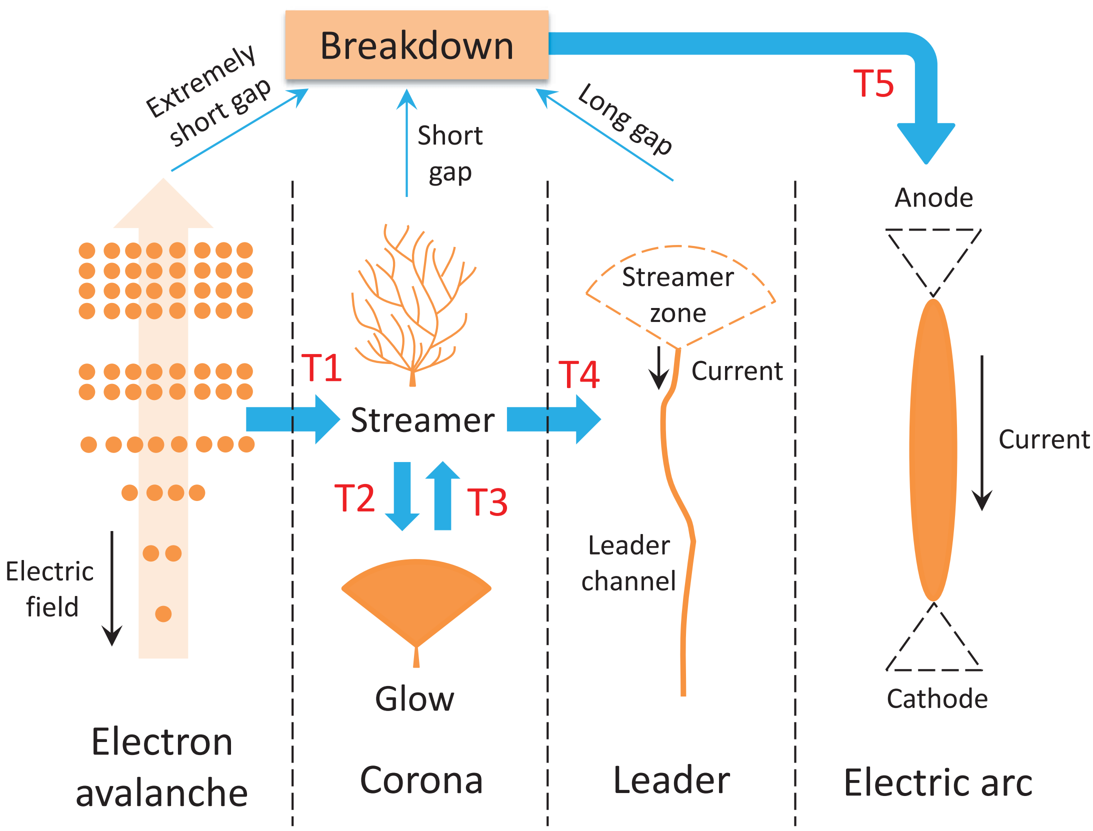


Figure 1.6 Conceptual sketch of different forms of electrical discharges and their transitions under atmospheric pressure.

# 1.4 The motivation and context of this thesis

## 1.4.1 The motivation and aim

As mentioned before, electrical discharges have a long research history. However, our knowledge of electrical discharges is still limited and many questions are still unsolved. Let us take the most common and famous phenomenon of lightning as an example. Several hundreds of years have passed after Benjamin Franklin conducted his experiments on lightning. Nevertheless, one of the most basic and important questions of 'how lightning is initiated' is still unsolved [1]. Another basic process poorly understood is the attachment of lightning flashes to grounded objects [42]. Although numerous models have been developed to describe this process, the accurate simulation of the interaction of lightning flashes with structures on the ground is still challenging [43]. Since lightning attachment is a complex physical process, the existing models use rather crude approximations of the different electrical discharges involved in order to reach a practical quantitative evaluation. However, the simplifications assumed by these models, particularly those used to evaluate the transitions between the different discharges, are still controversial. Hence, the debate on the effect of glow corona on the lightning attachment has not been concluded yet, mainly due to the lack of understanding of its transition into streamers [44]. Furthermore, quantitative estimates of the condition necessary for streamers to transform into leaders are still doubtful, especially when evaluating the attachment process after a first lightning strike [45]. Thus, an opportune project to contribute to the research on lightning and other applications is to investigate the physics behind these transitions.

This thesis aims to develop and use numerical simulation models in order to improve the physical understanding of two electrical discharge transitions in air at atmospheric conditions, namely the glow-to-streamer and the streamer-to-leader transitions marked respectively as T3 and T4 in figure 1.6. Even though other electrical discharge transitions are mentioned briefly in the text, they are outside the scope of this thesis. This is because other transitions either are rather well understood or require too much work to go one step further. For example, The first two-dimensional simulation of the avalanche-to-streamer transition in a uniform field was performed by Dhali and Williams in 1987 [46], followed by numerous simulations reported in the literature such as [47-52]. The transition from avalanches to a single filamentary streamer is rather well understood. It is widely accepted that the most important mechanism to provide secondary electrons in the avalanche-to-streamer transition is photoionization by ultraviolet photons [53], as illustrated in figure 1.3 (b). In air where oxygen concentration is high (～21%), photons emitted by excited nitrogen can ionize oxygen molecules [51]. While in pure nitrogen or in nitrogen with extremely low oxygen concentration, it has been suggested that the predominant mechanism to provide photons is the Bremsstrahlung (deceleration radiation) process instead [54]. The next major breakthrough on the research on the avalanche-to-streamer transition might be the understanding of the branching mechanism. However, a systematic explanation for this problem is very difficult and challenging to accomplish [18, 52].

The first one-dimensional (1D) simulation of the streamer-to-glow transition under a sudden applied DC voltage was conducted by Morrow in 1997 [41]. In the simulation, Morrow observed ‘streamer-like’ ionizing waves were produced from a stable glow corona if the applied voltage was raised rapidly [41]. However, streamers have filamentary structures that cannot be described with a 1D model. Since the simulation of the transition is a multiscale problem which is extremely time-consuming even in 1D, **Paper I** and **Paper II** in the thesis have been aimed to develop a numerical algorithm to efficiently solve corona discharge models. Based on this algorithm, a detailed two-dimensional (2D) model is used in **Paper III** to describe the physics of the glow-to-streamer transition. Since the evaluation introduced in **Paper III** is still impractical for the analysis of real objects in lightning attachment studies, **Paper IV** is intended to develop a simplified model which can properly take into account the relevant physical processes within the transition.

On the other hand, the streamer-to-leader transition occurs not only in front of the electrode before leader inception, but also at the tip of a propagating leader. Although the transition during the leader propagation is well understood [20, 55-57], the transition dynamics before the inception of a stable leader has been less studied. This is the main motivation of **Paper V**.

**Paper VI** and **Paper VII** introduce the first implementation of the model presented in **Paper III** towards the analysis the transition of glow corona into streamers initiated from shielding wires and lightning rods. These papers are aimed as a first step to the physical analysis of the effect of glow corona on lightning attachment, especially for unusual lightning strikes observed in UHV transmission lines and the lightning rods [44].

### 1.4.2 The method and structure

The main method to perform the study of these electrical discharge transitions is through numerical modelling and simulation. Depending on different scenarios, different simplification and assumptions are used. Compared to the research through laboratory experiments, the most obvious advantage of numerical simulations is that it can provide detailed information on the microscopic and transient parameters, which are very difficult to measure. However, the proposed numerical models need to be first validated by comparison with the measured macroscopic parameters reported in the literature such as the current-voltage characteristics before they are used.

The main content of the thesis is divided into additional six chapters. The 2D simulation of the glow-to-streamer transition is a challenging problem from the perspective of numerical techniques. To do this, **Paper I** and **Paper II** proposed an efficient numerical algorithm for corona discharge simulation. Chapter 2 introduces the numerical challenges in the numerical modelling of corona discharges and summarizes **Paper I** and **Paper II**. Chapter 3 describes **Paper III** which deals with the physics of the glow-to-streamer transition. In addition, an efficient and simplified physical model for glow corona discharges proposed in **Paper IV** is also introduced. The dynamics of the streamer-to-leader transition during leader inception presented in **Paper V** is summarized in Chapter 4. Chapter 5 introduces **Paper VI** and **Paper VII** where the glow-to-streamer transition in the lightning attachment process is analysed. Conclusions and future work are presented in Chapter 6 and 7, respectively.

### 1.4.3 Author's contribution

The author of the thesis is the first and communication author of **Papers I-VII**. The idea and the solution algorithm for **Paper I** and **Paper II** were proposed by the author. The research questions and scientific approach for the remaining papers were proposed by the author and the supervisor. The development of all the computer code and the writing of most part of the papers were performed by the author.

# 2 Towards an efficient numerical algorithm for corona discharge simulations

"*Gōng yù shàn qí shì，bì xiān lì qí qì.*"

from *Lúnyǔ* (expressed in Chinese *Pinyin*)

"*A workman must sharpen his tools if he wants to do his work well.*"

from *Analects of Confucius* (translation in English)

All the different forms of electrical discharges are essentially initiated from electron avalanches. They have multiscale properties not only in space (from nm to km) but also in time (from ns to s) [17]. The 3D structures of most discharges, such as the branching of streamers, make their modelling challenging. Feasible modelling of electrical discharge has to meet at least two conditions. First, the related physics have to be included, either with a complicated or a properly simplified model. Second, the model can be numerically solved within an acceptable time.

Electrical discharges are usually modelled in two different ways. The first one follows a kinetic or particle description such as in Monte Carlo or Boltzmann transport simulation, which has a resolution into the particle [14, 52] or superparticle-level [58]. Generally, the kinetic models are highly time-consuming [59]. The other approach is the fluid model, which is computationally more efficient and therefore is widely used in the literature [7, 60]. The fluid model of gas discharges is defined by several continuity equations (to account for the development of the relevant species) coupled with Poisson’s equation (to account for the distortion of the electric field by the generated space charge) [7]. The fluid model for corona discharges is based on several important assumptions [7], including the local field approximation which assumes that the electron energy distribution function is in local equilibrium with the background gas. Theoretical analysis [48] and numerical experiments comparing particle and fluid models [59, 60] have shown that the assumptions of the fluid model generally holds and therefore it can be an alternative to the particle model [7].

In this chapter, the numerical challenges of solving the fluid model are described and an efficient numerical algorithm for corona discharges proposed in **Paper I** and **Paper II** is introduced.

## 2.1 The simplest model for corona discharges in air

For cold plasmas like corona discharges, the effect of air heating is usually neglected such that constant air temperature and pressure are assumed. An exhaustive description of the kinetics of corona discharges in dry air is difficult [61] and even more complex in humid air. Since the numerical simulation with a detailed kinetic scheme is very time-consuming, simplified models are usually used. The simplest model usually assumes that corona discharges are composed only of electrons, positive and negative ions, and excited species considering averaged reaction rates [62]. The set of continuity equations describing these species in air is reprinted from **Paper III** as

$$\frac{\partial N_e}{\partial t} = S_{\mathrm{ph}} + (\alpha - \eta) N_e |\boldsymbol{W}_e| - \beta N_e N_p + k_d O_2^* O_2^- - \nabla \cdot [N_e(\boldsymbol{W}_e + \boldsymbol{w})] \tag{2.1}$$

$$\frac{\partial N_p}{\partial t} = S_{\mathrm{ph}} + \alpha N_e |\boldsymbol{W}_e| - \beta N_e N_p - \beta N_p N_n - \nabla \cdot \left[N_p(\boldsymbol{W}_p + \boldsymbol{w})\right] \tag{2.2}$$

$$\frac{\partial N_n}{\partial t} = \eta N_e |\boldsymbol{W}_e| - k_d O_2^* N_n - \beta N_p N_n - \nabla \cdot [N_n(\boldsymbol{W}_n + \boldsymbol{w})] \tag{2.3}$$

$$\frac{\partial O_2^*}{\partial t} = \alpha_m N_e |\boldsymbol{W}_e| - k_d O_2^* N_n - k_q O_2^* O_2 - \nabla \cdot (O_2^* \boldsymbol{w}) \tag{2.4}$$

where $t$ is the time, $N_e, N_p, N_n, O_2$ and $O_2^*$ are the number densities of electrons, positive ions, negative ions, oxygen molecules and metastable oxygen molecules, respectively. $\boldsymbol{W}_e, \boldsymbol{W}_p, \boldsymbol{W}_n$ are the drift velocities for electrons, positive ions and negative ions taking the background air as a reference. $\boldsymbol{w}$ is the bulk velocity of background gas accounting for air flow. Diffusion of all the particles is neglected since it plays a negligible role. The symbols $\alpha, \eta, \beta, \alpha_m$ denote the ionization, attachment, recombination coefficients and the rate of creation of metastable molecules, respectively. $k_d, k_q$ are the detachment rate coefficient and quenching rate constant, respectively. $S_{\mathrm{ph}}$ is the photo-ionization rate. The transport parameters and reaction rates in air are summarized in the appendix of **Paper III**.

The continuity equations are fully coupled with Poisson's equation expressed as

$$\nabla \cdot E = \frac{e}{\varepsilon}\left(N_p - N_n - N_e\right) \tag{2.5}$$

where $\varepsilon$ is the permittivity of air, $e$ is the electron charge and $E$ is the electric field. There are several challenges in solving the above fluid model. In the next subsection, these challenges are described briefly.

## 2.2 Numerical challenges in solving the fluid model

The numerical modelling of electrical discharges is an interdisciplinary task, which requires knowledge of plasma physics, computational fluid dynamics (CFD) and computational electromagnetics. For electrical discharge simulations, a suitable numerical method has to consider several aspects such as the accuracy and efficiency in solving the continuity and Poisson equations, the flexibility in handing irregular geometries, and the extensibility to high dimensions. In other words, a suitable numerical method should

- be able to provide accurate and positivity-preserving solutions for the density profile of the modelled species when solving continuity equations since negative density solutions do not have any physical meaning;
- be able to efficiently solve Poisson's equation since it is highly coupled with the continuity equations and it is calculated at each time step within a simulation;
- be able to handle unstructured meshes since the geometries where electrical discharges present are often irregular such as point-to-plate configuration; and
- be easily extended to high dimensions and other coordinate systems for example cylindrical coordinate system which is frequently used due to axis symmetry since 3D modelling is much more time-consuming.

There are several challenges when developing such a method. The first challenge comes from the solution of continuity equations, which evaluate the variation of the density of the modelled species. In general form, it is expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\boldsymbol{u}\rho) = S \qquad (2.6)$$

where $\rho$ and $\boldsymbol{u}$ are the number density and velocity of the modelled specie. $S$ accounts for the sources and sinks due to reactions with other species. In electrical discharges, charged species drift very fast under the electric field while the diffusion is much weaker. For such kind of convection-dominated problems, the diffusion is usually neglected.

It is a challenge to solve continuity equations accurately since very sharp gradients in density and velocity can also appear for example in the front of streamers (see **Paper II**). Under these conditions, conventional numerical methods may encounter artificial numerical oscillations or excessive numerical diffusion. Figure 2.1 shows an example of the simulation results for a square test with the finite difference method (FDM) of first and second order. The square test in the field of CFD simply means simulating the drift of a square profile of density under a constant velocity field without any loss. It has been widely used in the CFD area since the analytic solution is straightforward while the accurate numerical solution is difficult due to the very sharp gradient at the edge of the square profile. As shown in figure 2.1, the first order upwind method has serious numerical diffusion compared to the analytic solution, while the second order scheme is less diffusive but has numerical oscillations.

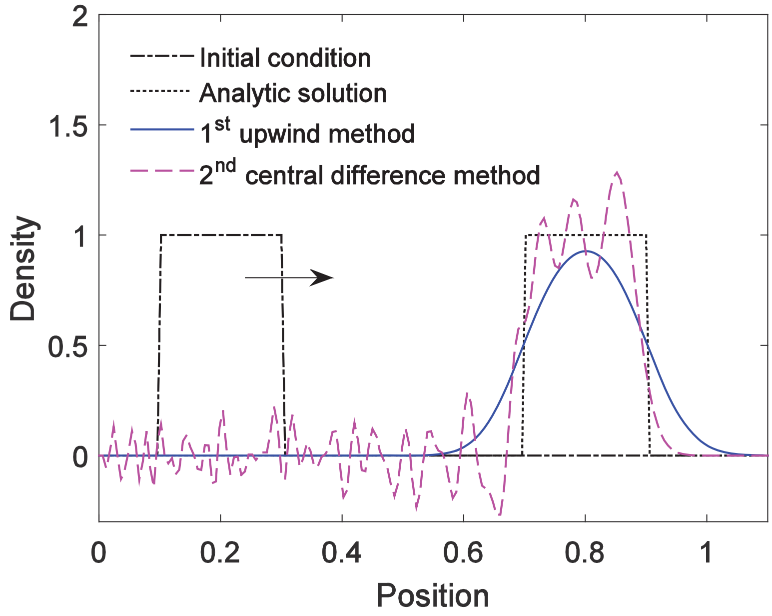


Figure 2.1 Comparison between the simulated results and the analytic solution in a square test.

One idea to improve the numerical method is to combine the advantages of both low order and high order schemes, which was first introduced by Boris and Book in 1970s. They developed the flux-corrected transport method (FCT) [63-65], which later was successfully applied to the 2D simulation of the streamer propagation [46]. For a brief review of other numerical methods used in the literature for corona discharge simulation, the reader is referred to the introduction in **Paper I**.

The second challenge comes from the efficient solution of Poisson's equations. Different methods have been used in the literature, for example, the fast Fourier transform algorithm [46], the symmetrical successive over-relaxation method [66], and the direct SuperLU solver [67]. However, it is challenging to use FDM or the finite volume method (FVM) to solve Poisson's equations on unstructured meshes since the discretization is more complicated than for structured meshes [68]. The most suitable method to handle irregular geometries using unstructured mesh is the finite element method (FEM). FEM combined with FCT [69] and diffusive stabilization techniques [70, 71] have also been successfully employed in corona discharge simulations, such as in [72] and [73]. However, these methods are not inherently positivity-preserving and numerical oscillations can take place without extra imposed conditions.

## 2.3 An efficient numerical algorithm for corona discharges

### 2.3.1 The position-state separation method

The aim of electrical discharge modelling is to calculate accurately the density of any specie in space at any time. In other words, the simulation task is finished once the species are solved as a function of time, position and state. When solving the continuity equation, challenges arise since both the time and space discretization of the density are mixed in one equation. To circumvent this, the transient solution of the position and the state of the density can be split into two subproblems: the state equation which describes the state change and the position equation which deals with the drift effect only. For example, equation (2.6) can be divided into two different equations: the state equation

$$\frac{\partial \rho}{\partial t} = -\rho \nabla \cdot \boldsymbol{u} + S \tag{2.7}$$

which deals with the variation of the variable $\rho$ due to convective acceleration and the reaction terms; and the position equation

$$\frac{\partial \rho}{\partial t} + \boldsymbol{u} \cdot \nabla \rho = 0 \tag{2.8}$$

which determines the transport of the variable $\rho$ by considering the linear convection only.

The state equation (2.7) can be solved on an appropriate mesh (named as the reference mesh) to obtain the new density profile $\rho^*$ at the next time step. This can be done with any conventional numerical method because the discretization of space and time is performed for different variables, i.e., $\rho$ and $u$ in equation (2.7) respectively. The position equation (2.8) can be easily solved by integrating the ordinary differential equation

$$\frac{\partial \boldsymbol{x}}{\partial t} = \boldsymbol{u} \tag{2.9}$$

along the characteristic lines of the drift, resulting in a new mesh (named as the auxiliary mesh). The state on the reference mesh can be obtained by interpolation from the auxiliary mesh with the updated density $\rho^*$. For a detailed description of POSS, the reader is referred to **Paper I**.

### 2.3.2 Applications to simulate glow and streamer discharges

One of the challenges for POSS is that the used linear interpolation is not mass-conserving, which means the solution has serious numerical diffusion if very small time step is used, as shown in **Paper I**. There are mass-conserving or shape-conserving algorithms available in the literature such as [74]. However, mass-conserving interpolation on unstructured meshes is complicated and time-consuming. The efficiency of POSS will be significantly reduced if mass-conserving interpolation is used.

For glow corona discharges where the electric field changes slowly with time, large time step can be used for POSS and thus the numerical diffusion caused by the interpolation can be neglected. In **Paper I**, the POSS method has been successfully applied to simulate the formation of positive glow discharges in a 1D co-axial spherical configuration under a DC voltage. POSS is very efficient when simulating glow corona discharges since the required time step can be much larger than that restricted by the Courant–Friedrichs–Lewy (CFL) condition. Furthermore, POSS does not require the ‘flux correction’ procedure which is usually very time-consuming on unstructured meshes.

However, very small time steps have to be used for streamer simulation where electric fields change dramatically. In such a case, the chosen time step is determined by physical characteristic times instead of being limited by the stability of the numerical algorithm. Under such conditions, POSS will encounter excessive numerical diffusion caused by the interpolation step, as shown in **Paper I**. In order to solve this problem, a multi-step interpolation strategy is introduced in **Paper II**. The idea is to use a small time step to capture the physical changes and use a larger time step for interpolation to avoid serious numerical diffusion. Several reproducible streamer simulations in the literature are selected as benchmark tests to show that POSS combined with FEM is a competitive alternative method to simulate streamer discharges, especially in complex geometries. Although it is difficult to compare different methods used to simulate streamers in the literature, a general evaluation of different methods is possible. **Paper II** compares the total computation time used in different methods. It is shown that the computation time with POSS is significantly less than other approaches such as FEM-FCT and FVM-MUSCL (monotone upstream-centered schemes for conservation law) [75]. Furthermore, POSS is more robust than other FEM method such as FEM-FCT since it is inherently positivity-preserving as shown in **Paper I**.

# 3 Physics of the glow-to-streamer transition in air

"*Enter through the narrow gate; for the gate is wide and the road is easy that leads to destruction, and there are many who take it. For the gate is narrow and the road is hard that leads to life, and there are few who find it.*"

from *Matthew* 7-13,14

In industrial applications involving glow corona such as in ozone production, the generated discharge should be as homogeneous as possible to obtain a high collision rate between electrons and the background gas molecules [7]. In this way, the products yield can be increased and the power consumption reduced. [76]. For this reason, the glow-to-streamer transition has to be avoided. Glow discharges also occur in nature during thunderstorms as mentioned in section 1.1. The space charge generated by glow corona can significantly change the electric field distribution around grounded objects. As thunderstorms further develop, upward streamers and leaders can be subsequently initiated such that the shielding of the pre-existing glow space charge can play an important role. Thus, it is interesting to investigate the conditions required for the glow-to-streamer transition to occur.

The layer where intensive ionization occurs in front of the anode during corona discharges is usually difficult to simulate for long simulation times. One strategy to avoid the complexity of resolving the ionization layer is to use Kaptzov's approximation [77], which neglects the electron dynamics in the discharge and assumes a boundary condition to define the injection of unipolar ionic charges instead. The boundary condition forces the surface electric field to stay at the onset field once corona is initiated. Kaptzov's approximation has been widely used to evaluate the effect of corona space charge on the initiation of streamers under fast changing background electric fields [44, 78-81].

In the first part of this chapter, the investigation of the glow-to-streamer transition without using Kaptzov's approximation presented in **Paper III** is summarized. The second part is dedicated to introduce an efficient physical model for evaluating glow corona and the transition into streamers as proposed in **Paper IV**.

## 3.1 2D simulations of glow-to-streamer transition

### 3.1.1 The formation of positive glow corona

In order to assess the mechanism of the glow-to-streamer transition, it is worth to first understand the dynamics of glow corona discharges. The theory of positive glow corona was not well understood until the end of last century when Australian scientist Richard Morrow performed a pioneering 1D simulation [41]. The general dynamics of such a transition under a sudden positive DC voltage is summarized as follows:

- As the applied voltage to the inner conductor (anode) exceeds the onset voltage, the air close to the anode is ionized and pre-onset streamers are produced.
- Electrons and negative ions are absorbed by the anode while positive ions move to the outer conductor (cathode).
- As positive ions drift away from the anode, the electric field around the anode increases sufficiently to ionize again the nearby air, forming a new space charge layer.
- The above-described process is repeated until a stable glow corona discharge is produced, as shown in figure 3.1.

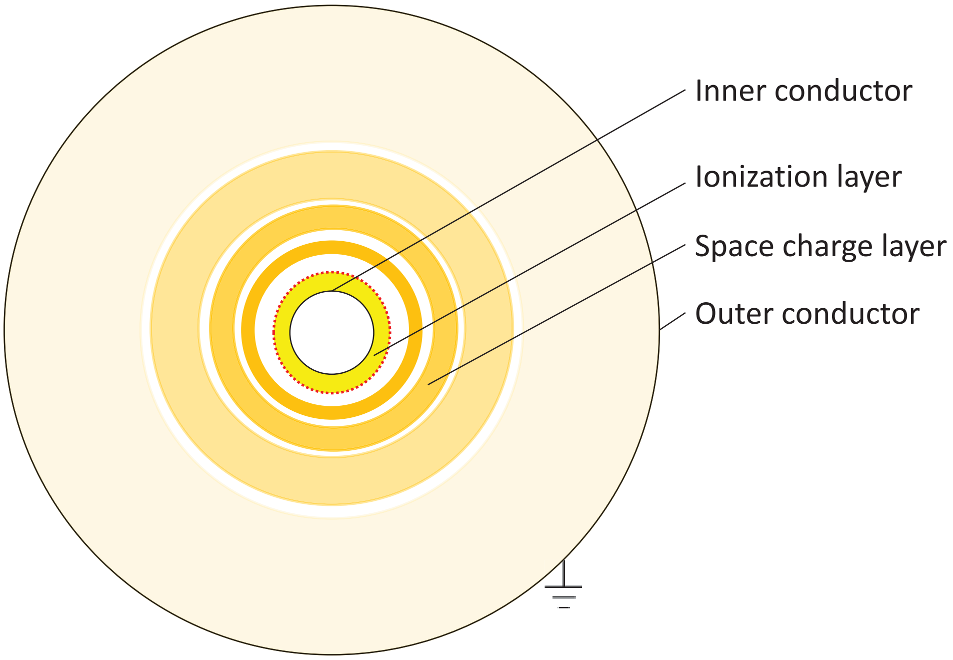


Figure 3.1 Sketch of the cross section view of a positive glow corona discharge under DC applied voltage in a coaxial cylindrical configuration.

Morrow extended the FD-FCT to a non-uniform mesh in order to simulate a stable glow corona in a spherical coaxial configuration with a 2 cm long air gap [82]. Nevertheless, such a 1D simulation took several days to finish for the several microseconds required to reach a stable glow [50]. The speed up the simulation of glow corona discharge including the ionization layer has been the main motivation to develop the POSS method earlier introduced in Chapter 2.

### 3.1.2 The mechanism of the glow-to-streamer transition

Morrow observed in his numerical experiments that (1D) streamer-like ionizing waves were produced from a stable glow corona if the applied voltage was raised rapidly [41]. However, streamers have filamentary structures that cannot be described with such a 1D model. As a first approach, **Paper III** performs a 2D simulation of the glow-to-streamer transition without Kaptzov's approximation. The POSS method proposed in **Paper I** is used to handle the difficulties associated to the convection-dominated continuity equations in the simulation.

In **Paper III**, the generation of glow corona under DC voltage is first simulated. Once the glow corona under DC voltage is formed, the applied voltage is raised with a constant dV/dt rate. Since the space charge generated by glow corona in a coaxial cylindrical configuration is uniformly distributed, the transition to filamentary streamers cannot be produced unless either physical or numerical instabilities are included in the model. In **Paper III**, three different types of instabilities are taken into account. It is shown that these instabilities do not change the critical dV/dt required for the transition when filamentary streamers are observed. The basic mechanism of the glow-to-streamer transition is described as follows:

- As the applied voltage is increased, the time for new produced positive ions to drift away is reduced.
- These ions accumulate around the surface of inner conductors, intensifying the local distortion of the space charge and the electric field caused by the introduced instability.
- The inhomogeneity of the electric field in turn further increases the distortion of the space charge due to increased ionization.
- The homogeneity of the layered structure of glow corona is destroyed by the formation of streamers.

One of the most interesting conclusions of **Paper III** is that streamers are easier incepted from blunt corona generating electrodes than from sharp ones. This is because the space charge drifts faster for sharper electrodes and thus the applied voltage has to be increased at a faster rate for the space charge to start accumulating.

## 3.2 Efficient model for glow discharges considering the ionization layer

The simulation of positive glow corona discharges with the fully-coupled physical model (FPM) introduced in section 2.1 is extremely time-consuming, even in 1D. First, a very small time step is required by the FPM to resolve electrons in the ionization layer since the electrons drift two orders of magnitude faster than ions. Second, a finer mesh is also required to discretize the ionization layer, further increasing the computational cost.

One strategy to simplify the simulation of corona discharges is to neglect the ionization layer and to use Kaptzov's approximation instead. Due to its simplicity, Kaptzov's approximation has been frequently in the literature [44, 83-85]. However, **Paper III** shows that Kaptzov's approximation does not hold under fast changing background electric fields.

Based on the detailed simulation of corona discharges with the FPM as presented in **Paper III**, it was found that a simplified physical model (SPM) for glow corona discharges can be formulated due to the following facts:

- Electron avalanches only take place in a well-defined layer where ionization exceeds attachment;
- The electrostatic conditions in the computation region are mainly defined by the ionic space charge since the density of electrons is more than two orders of magnitude smaller than for ions;
- Electrons are more than two orders of magnitude faster than ions; and
- The source terms of photo-ionization $S_{\mathrm{ph}}$, electron-ion recombination $\beta N_e N_p$ and negative ions detachment $k_d O_2^* O_2^-$ in the continuity equation for electrons (equation (2.1)) are several orders of magnitude smaller than the effective ionization $(\alpha - \eta) N_e |\boldsymbol{W}_e|$ in the ionization layer.

These facts allow us to assume that electrons reach quasi-steady state, i.e. $\frac{\partial N_e}{\partial t} = 0$ within the characteristic time of ion drift. It has to be emphasized that the quasi-steady state approximation for electrons here used is only valid for stable glow corona discharges.

**Paper IV** proposed the SPM to simulate glow corona discharges and their transition into streamers. The model is validated by performing comparisons with the FPM and with experimental data available in the literature for air under atmospheric conditions. It is shown that the SPM can obtain estimates similar to those calculated with the FPM and those measured in experiments but using significantly less computation time.

# 4 Physics of the streamer-to-leader transition in air

"*A theory is a supposition which we hope to be true, a hypothesis is a supposition which we expect to be useful; fictions belong to the realm of art; if made to intrude elsewhere, they become either make-believes or mistakes.*"

George Johnstone Stoney

Leader discharges exist in long air gap laboratory discharges [24, 39], troposphere lightning [1, 40] and upper atmosphere lightning such as blue jets and gigantic jets [16, 55]. A leader is a highly ionized, conductive and thermal channel with a temperature ranging between 2000 and 6000 K [23]. Leader discharges in the length of 1∼15 m can be produced in laboratory with high impulse voltages where detailed observations and measurements can be obtained. Laboratory experiments are important since a specific measurement with sufficient space and time resolution of a natural lightning event or a 'jet' is very difficult. The leaders in much larger scales (1-100 km) are believed to have similar characteristics as the leaders produced in the laboratory [16, 20, 40, 55]. In long air gap discharges in laboratory, extensively studied by the Les Renardières group in 1970s [86-89], the development of a positive leader discharge can be described as follows. First, the first streamer corona is incepted as the applied voltage increases. The electric field produced by the corona space charge counteracts the Laplacian field around the electrode, resulting in a dark period. Then, several secondary streamer discharges (streamer bursts) with dark periods in between may occur depending on the recovery of the electric field as space charge drifts into the space and the applied voltage increases. Second, a leader channel segment can be initiated if the gas temperature of any streamer stem reaches the critical value of about 2000 K. Third, the leader may continue propagating into the gap if the electrostatic conditions in front of the newly formed leader are sufficient. Otherwise, it will be aborted. Finally, leader breakdown takes place once the streamer corona at the leader tip reaches the opposite electrode, which is usually known as the 'final jump' [86].

The streamer-to-leader transition occurs in front of the electrode before the inception of leaders as well as at the head of a propagating leader. Although the transition during the leader propagation is well understood [20, 55-57], the transition dynamics before the inception of a stable leader has been less studied. This is the most important motivation to conduct the research presented in **Paper V**.

## 4.1 Dynamics of streamer-to-leader transition

In the previous studies of the streamer-to-leader transition during leader propagation [20, 55-57], a 1D thermo-hydrodynamic model was used. The model describes the cross section of the streamer stem with a 1D radial coordinate system by neglecting axial variations and assuming a constant current flowing in the axial direction. The radial electric field is neglected while the axial field is computed from the current and conductivity of the cross section using Ohm's law. Several features of the streamer-to-leader transition during leader propagation from these studies can be summarized as: (1) the stem of the streamer corona has to reach temperatures larger than about $1\,500 \sim 2\,000$ K in order to initiate a leader discharge. (2) The stem is heated by the sum of the current produced by the streamers within the streamer zone through Joule heating. (3) The heating process is governed by the contraction of thermal channel which is triggered by a thermal-ionizational instability.

Several additional modifications to the thermo-hydrodynamic models available in the literature are made in **Paper V** according to the facts described as follows. First, the 1D model has limitations to estimate the density of charged species during the dark periods due to the axial variation of the electric field in front of the electrode. These variations cause changes of density for electrons and ions along the axial direction which cannot be calculated. Second, experiments with Schlieren photography [90] have recently shown that a single solitary stem is not necessarily formed before a leader is incepted under switching voltage waveforms. Instead, several stems connected to the electrode can be produced by a streamer, through which the streamer current is shared. Third, the initial condition of previous studies [20, 55-57] usually assumes a fixed electron peak density ($2 \times 10^{14}$ cm$^{-3}$) and the simulation results are extremely sensitive to the initial radius since the current density of the stem changes significantly with the initial radius.

In **Paper V**, the analysis of the streamer-to-leader transition includes the simulation of the corresponding streamer bursts, dark periods and aborted leaders that may occur. The simulations are performed using as input the time-varying discharge current in two laboratory discharge events reported in the literature [90], which are used as case studies. The initial condition is defined according to the inception electric field instead of using a fixed electron peak density. During the dark period after the streamer stops propagating, the density of all the charged species are set to low background levels such that no joule heating occurs during the dark period. Since the electric field does not affect the energy relaxation by neutral species in the gas, their chemistry dynamics can be simulated during the dark period. Moreover, the corona current in this simulation is simply divided by the number of stems (assumed to be electrically similar) according to Schlieren photography [90]. In **Paper V**, excellent agreement between the estimated and experimental thermal radius for a 1m rod-plate air gap discharge has been found.

Another interesting conclusion found in **Paper V** is that the gas at the axis has to reach a temperature much larger than the critical value (of 2000 K) to initiate a stable leader that can propagate into the gap. This is because the gas temperature can drop due to very strong convection losses taking place soon after the streamer-to-leader transition. If the temperature after the drop falls below the critical value, the leader is aborted since the thermalization cannot be sustained. On the contrary, the leader can propagate if the gas temperature after the transition is higher than 2000 K after the convection loss.

## 4.2 The effect of humidity on the streamer-to-leader transition

At standard temperature and pressure (STP) conditions, the concentration of water molecule ($H_2O$) can reach up to 3% ($\sim 22\ \mathrm{g\ m^{-3}}$). It seems that such a low percentage of $H_2O$ can hardly affect the whole discharge processes. However, experiments indicate that humidity does play an important role [88, 91].

In order to investigate the effect of humidity, **Paper V** proposed a detailed kinetic scheme for $N_2/O_2/H_2O$ mixtures. The kinetic scheme includes the most important reactions with the $H_2O$ molecule and its derivatives, resulting in a scheme with 45 species and 192 chemical reactions. The effect of humidity on the electronic power partitioning and the vibrational energy relaxation are also discussed and included in the model.

It has been suggested in the literature that humidity plays a significant role on the thermalization of air through the V-T (vibrational-translational) relaxation [39]. However, the simulations in **Paper V** show that the V-T relaxation has a weak effect on the gas heating due to two main reasons. First, humidity weakly increases V-T relaxation and this effect becomes weaker in the following discharges. Second, the V-T relaxation power has a minor effect in the energy balance before a leader is formed since it is several orders of magnitude smaller than other energy sources during most of the streamer-to-leader transition. However, this conclusion is based on the assumption that humidity does not affect the current density of a stem. Even though it is known that humidity reduces the total charge injected by streamers [39, 88], there is unfortunately no experimental or theoretical knowledge about the effect of humidity on the current density of stems. Figure 4.1 shows an example of the photograph of streamer corona discharges in dry and humid air condition. As it can be seen, humidity plays an important role in streamer corona discharges [91]. The observations indicate that further studies on the formation of the streamer stem are required to fully assess the effect of water content on the streamer-to-leader transition.

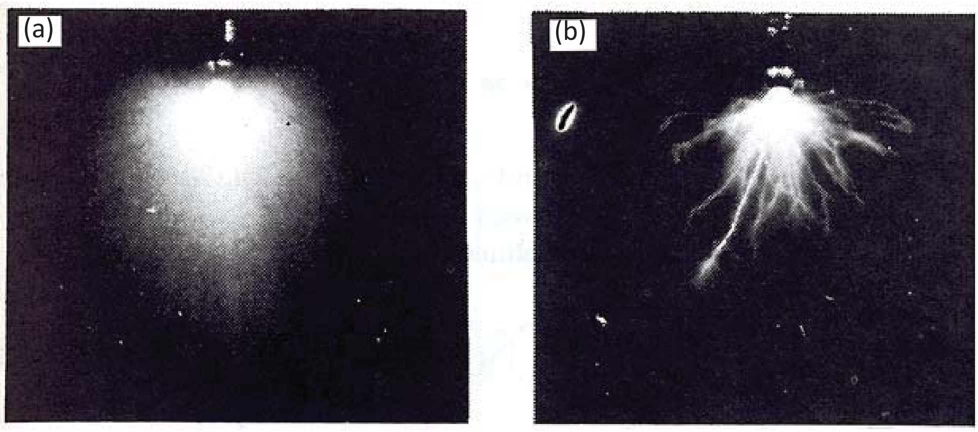


Figure 4.1 Influence of humidity on streamer corona discharges in a 0.9 m rod-plane gap. (a) $5\ \mathrm{g\ m^{-3}}$ (b) $32\ \mathrm{g\ m^{-3}}$. Images adapted from [91] with permission.

Laboratory experiments have shown that humidity can significantly reduce the duration of the dark period [39]. **Paper V** indicates that humidity weakly influences the dynamics of the stem as long as the same initial conditions and input discharge current are used in the simulation. Thus, the effect of humidity on the dark period appears to be mainly explained by the reduction of the electrostatic shielding produced by the streamer space charge.

In **Paper V**, the developed model is also compared with the widely-used model of Gallimberti. The model proposed by Gallimberti was derived considering several simplifying assumptions, for example, the electric field of the stem was assumed constant, the radial variations of the chemistry and the gas flow were neglected and the vibrational-translational relaxation was simplified with an equivalent time constant as a function of temperature and humidity only. However, the simulation and analysis performed in **Paper V** show that the assumptions used by the model of Gallimberti do not hold when evaluating the streamer-to-leader transition.

# 5 Application case study: analysing unusual lightning strikes

"*Physics is, hopefully, simple. Physicists are not.*"

"*The science of today is the technology of tomorrow.*"

Edward Teller

As mentioned in section 1.1, lightning is a threat to tall grounded structures such as buildings, UHV power transmission lines and wind turbines. The belief that lightning was so powerful that only gods and goddesses could generate and control it dominated early civilizations [92]. Since the mid-eighteenth century, science has helped to explain the nature and formation of lightning [93]. From then on, different lightning protection methods are used to protect these structures against lightning strikes. For example, power transmission lines are protected by shielding lines (earth lines) and tall buildings are protected by lightning rods. However, it is found that these devices sometimes can fail to protect a structure. This is generally known as a lightning shielding failure.

Thunderclouds are usually negatively charged and produce a background electric field $E_b$ up to for example 20 $\mathrm{kV\,m^{-1}}$ near the ground [94]. During thunderstorms, high voltages can be induced at the tips of tall grounded objects. As a result, positive glow corona can be initiated as it has been mentioned in section 1. With the presence of a downward lightning leader approaching these glow generating objects, upward streamers can be initiated (glow-to-streamer transition), followed by the inception of upward lightning leaders (streamer-to-leader transition).

It is widely known that the space charge generated by the glow corona can weaken and smooth the electric field around corona-generating surfaces. It is of great interest to know the effect of space charge on the glow-to-streamer transition, which has been previously studied with 1D models [56, 78-80, 95-101] and 2D models [44, 83] using Kaptzov's approximation. One of the motivations of **Paper III** is to investigate the effect of space charge without using Kaptzov's approximation, i.e., with consideration of the ionization layer. The idea has been used to analyse the effect of space charge on the glow-to-streamer transition for horizontal conductors and lightning rods in **Paper VI** and **Paper VII**.

In this chapter, the work of **Paper VI** and **Paper VII** is summarized. Unusual lightning strikes to tall grounded structures are discussed.

# 5.1 Observations of unusual lightning strikes

## 5.1.1 Lightning shielding failure in tall structures

The electrogeometric method (EGM) [102] has been widely used to evaluate the lightning protection of transmission lines due to its simplicity and fair agreement with early field observations [103]. The EGM method calculates the geometric exposure zone of a conductor to downward lightning leaders according to the prospective return stroke peak current ($I_\mathrm{p}$). The exposure zone is determined by an arc with radius $r_\mathrm{s}$ from the conductor surface, as shown in figure 5.1. The radius $r_\mathrm{s}$ is calculated with an empirical formula expressed as $r_\mathrm{s} = aI_p^b$, where $a$ and $b$ are coefficients tuned based on field observations.

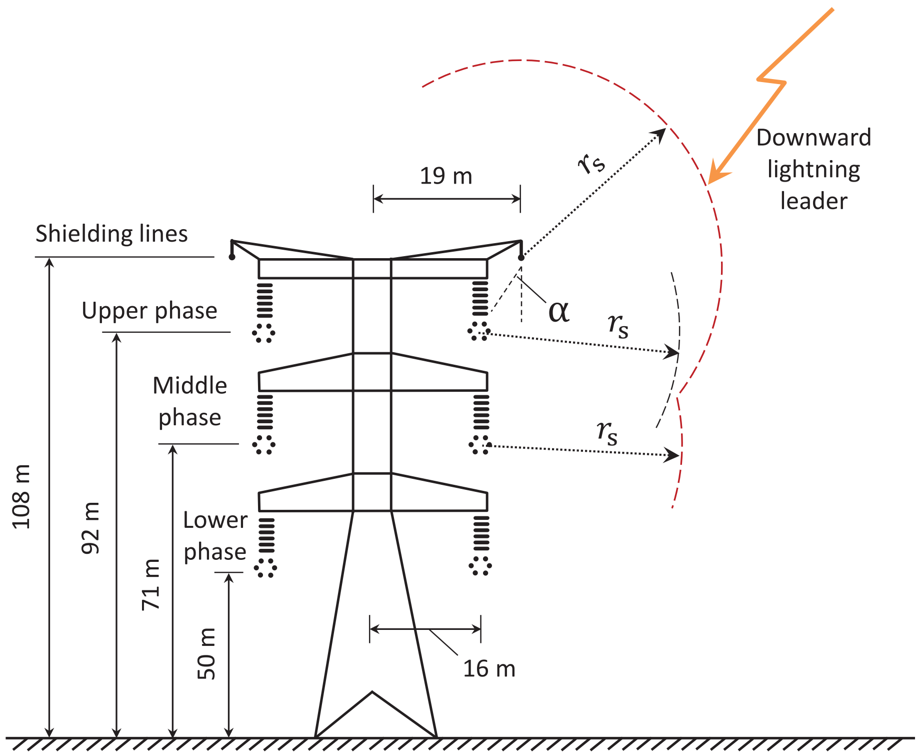


Figure 5.1 Sketch of the cross section view of a typical UHV transmission lines used in Japan and the lightning exposure zone calculated from EGM.

As shown in figure 5.1, shielding wires are generally arranged on the outside of phase conductors forming a negative protection angle [102]. In this way, the shielding wires should be able to protect well the phase conductors according to the EGM, at least for the upper phase lines as shown in figure 5.1. However, shielding failures for ultra-high voltage power transmission lines have been observed as shown in figure 5.2. Similar shielding failures have also been reported for tall towers. For example, figure 5.3 shows that the lightning termination at the tip of a tower sometimes can fail to protect the tower itself [40].

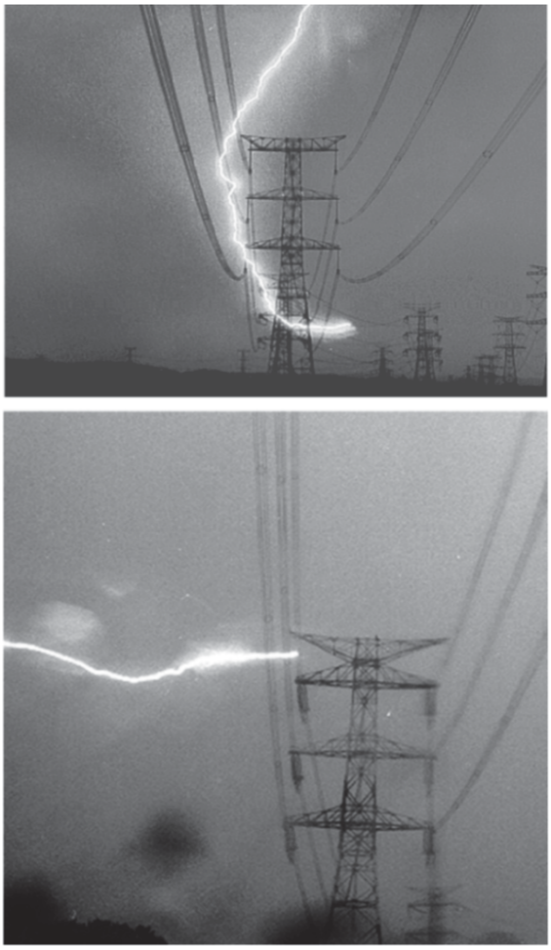

Figure 5.2 Lightning stroke to the upper phase of a UHV transmission line (operated at 500 kV). Photographs were taken on July 22, 2000 (top) and July 9, 1998 (bottom), respectively. Photographs reprinted from [104] with permission © IEEE 2007. The cross section view of the tower shown in the top image is given in figure 5.1.

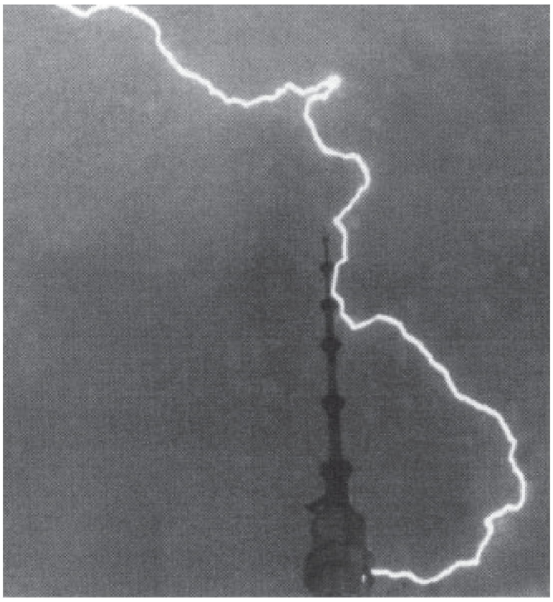

Figure 5.3 The lightning stuck the Ostankino Television Tower over 200 m below its top. Photograph reprinted from [40] with permission.

## 5.1.2 Competition study of lightning receptors

In 1990s, Moore and his team conducted a series of field experiments aiming to investigate the performance of Franklin rods [105, 106]. The lightning rods with different radii were installed on about 3300 m high mountains in New Mexico, US. The lightning rods are arranged with several meters distance between each other, as show in figure 5.4 (a). Their results show that none of the sharp rods with diameter $D$ < 1 cm or too blunt rods with diameter $D$ > 5 cm was struck in seven summer thunderstorm seasons. On the contrary, all lightning strikes were received by moderate blunt rods, as shown in figure 5.4 (b). These field observations are counter-intuitive because sharp-tipped rods are generally viewed as more efficient lightning receptors since the electric field around them is higher and strongly non-uniform.

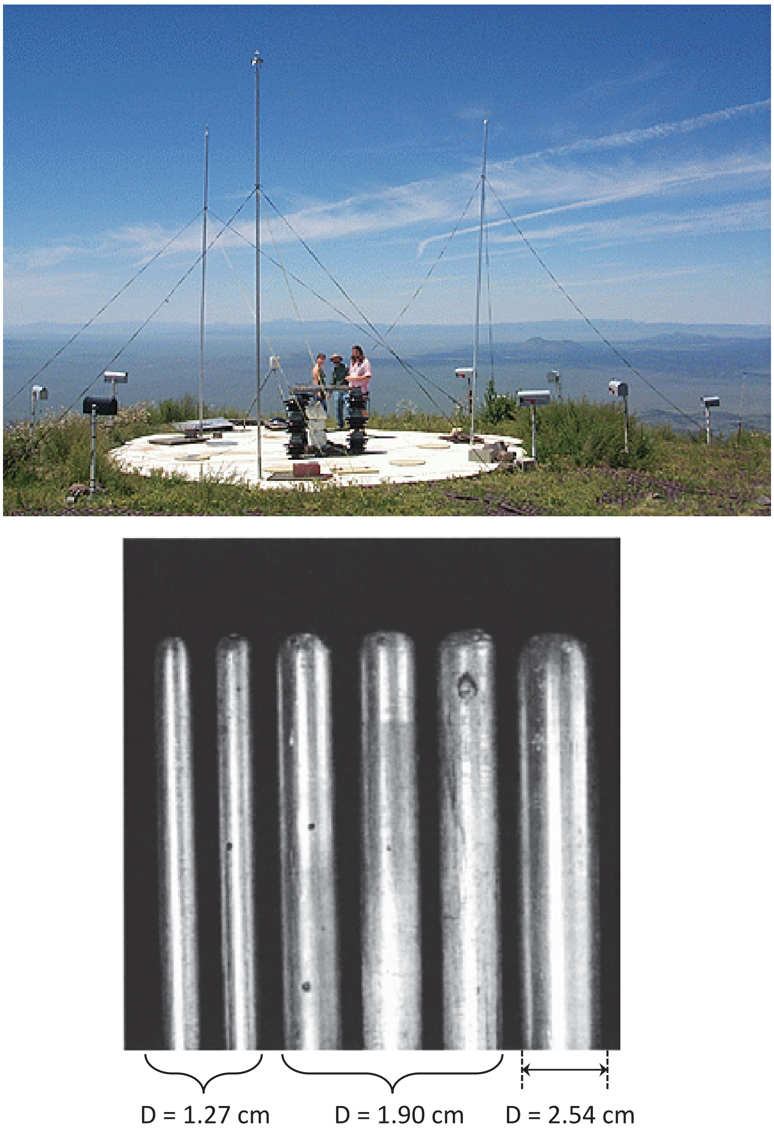


Figure 5.4 (a) Photograph of the experimental setup and (b) photograph of six blunt lightning rods used in the field tests conducted by Moore *et al* [105]. The images are reprinted from [105] with permission.

## 5.2 Effect of the glow-to-streamer transition in lightning strikes

Section 5.1 presented several field observations showing that lightning can strike grounded structures in an unusual way, especially when they are very tall ($\gtrsim$ 100 m) or they are installed on high buildings or mountains. There are only a few explanations to unusual lightning shielding failures in the literature. For example, the shielding failure of the TV tower shown in Figure 5.3 has been attributed to the stochastic nature of lightning [40]. In order to qualitatively complement the existing analyses of such observations, a first evaluation of the glow-to-streamer transition in the attachment of lightning to grounded objects has been presented in **Paper VI** and **Paper VII**.

Thus, UHV transmission lines are modelled as perfectly cylindrical, coaxial and grounded conductors in **Paper VI**. Since bundle conductors are usually used in UHV transmission lines to reduce the energy loss due to corona discharge, the glow-to-streamer transition from a scaled bundle conductor is firstly studied. It is found that the bundle conductors could be viewed as a single conductor with the equivalent geometric mean radius of the wire configuration when evaluating the condition required for the glow-to-streamer transition. As concluded in **Paper III**, it is easier for streamers to be incepted from blunt corona generating electrodes than for sharp ones. Thus, it becomes easier for the glow-to-streamer transition to take place from the phase conductors since the geometric equivalent radius is significantly larger than the physical conductor radius, as estimated in **Paper VI**. However, this conclusion is based on several simplifications as noticed in **Paper VI**. In reality, the asymmetry of the transmission lines, the protrusions on the conductors, the wind or rain, the operating voltage, and the 3D geometry of the transmission lines and the downward lightning leaders might also play an important effect on the conditions for the glow-to-streamer transition to take place.

Similar analysis applies to the case of the lightning shielding failure to the TV tower shown in Figure 5.3. In **Paper VII**, a scaled lightning rod with cylindrical body and hemispherical tip (as used in Moore's experiments [105]) is modelled. The numerical simulations show that streamers can be incepted from the body of a lightning rod under the influence of downward stepped leaders, even a distant one. Thus, it can be easier for streamers to be incepted from the body of a grounded tower rather than from its tip. Similar to the above explanations, the observations taken by Moore *et al* can also be partially explained by the effect of glow corona. The photographs in figure 5.4 (b) show that lightning can also strike to the body of the rod as implied and predicted by the simulations in **Paper VII**. However, further theoretical or experimental work is required to assess a full understanding of the observations.

# 6 Conclusions

In this thesis, the work of **Papers I-VII** is summarized aiming to provide a better physical understanding of electrical discharge transitions in air. The main work and conclusions are listed as below.

In **Paper I** and **Paper II**, an efficient semi-Lagrangian algorithm referred to as the position-state separation method (POSS) is proposed for the simulation of corona discharges. Several benchmark tests are conducted to demonstrate the low computational cost, robustness, and high-resolution of POSS to solve convection-dominated continuity equations. For the simulation of corona discharges where the velocity field is weakly changing in time, the solution with POSS is not restricted by the CFL condition when solving the continuity equations. Therefore, a time step significantly larger than that for explicit Eulerian methods can be used. POSS can also be used to simulate filamentary streamer discharges where electrical field changes dramatically in space and time. Without flux correction and combined with a finite element method, POSS is easy to be implemented on arbitrary geometries. In summary, POSS is an accurate, efficient and stable alternative method to simulate electrical discharges.

In **Paper III**, the 2D numerical simulation of the glow-to-streamer transition under a fast changing background electric field is presented. It is found that the surface electric field of a glow corona generating electrode deviates from the onset electric field. Therefore, Kaptzov's approximation does not hold and the ionization layer should be considered. During the glow-to-streamer transition, the electronic current increases significantly by at least two orders of magnitude within several hundreds of nanoseconds. The more glow corona space charge is generated from the electrode, the higher critical rate of rise of the applied voltage is required for the glow-to-streamer transition. Thus, it is easier for streamers to be incepted from blunt corona generating rods than from sharp ones.

In **Paper IV**, a simplified physical model (SPM) for simulation of glow corona and its transition into streamers is proposed. The SPM is verified by comparisons with the fully coupled physical model (FPM) and validated with experimental results available in the literature for discharges in air under atmospheric conditions. The SPM is proposed as a computationally efficient alternative to calculations of glow corona discharges based on Kaptzov's approximation. It is shown that the SPM can obtain similar results compared with the FPM for stable glow corona and its transition into streamers. With an efficient segregated numerical strategy to handle electrons, the SPM is three orders of magnitude faster than the FPM. This enables the efficient simulation of glow corona and the transition into streamers considering the ionization layer, even for configurations with large interelectrode gaps and for long simulation times.

In **Paper V**, the dynamics of streamer-to-leader transition prior to the leader initiation in long air gap discharges is investigated with a thermo-hydrodynamic model and a detailed kinetic scheme of $N_2/O_2/H_2O$ mixtures. It is found that although a small percentage of water molecules can accelerate the vibrational-translational relaxation to some extent, this effect leads to a negligible temperature increase during the streamer-to-leader transition. It is also found that the gas temperature should significantly exceed 2000 K for the transition to lead to the inception of a propagating leader. Otherwise, the strong convection loss produced by the gas expansion during the transition causes a drop in the translational temperature below 2000 K, aborting the incepted leader. Furthermore, it is shown that the assumptions used by the widely-used model of Gallimberti do not hold when evaluating the streamer-to-leader transition.

In **Paper VI** and **Paper VII**, 2D simulations on the glow-to-streamer transition are performed for horizontal conductors and lightning rods, respectively. It is suggested that it is easier for streamers to be initiated from corona generating bundle conductors than from single conductors. It is shown that a bundle conductor could be viewed as a single conductor with the equivalent geometric mean radius of the wire configuration when evaluating the critical rate of rise of the background electric field during thunderstorms. It is also concluded that the glow space charge generated by lightning rods cannot hinder streamers to be incepted under the fast changing background electric field produced during thunderstorms. For example, even with the presence of a distant downward stepped leader, streamers can be incepted from the body of the lightning rod. **Paper VI** and **Paper VII** indicate that glow corona generated from the tall grounded structures plays a significant role in the attachment of lightning to structures.

# 7 Future work

**Paper I** and **Paper II** proposed an efficient numerical algorithm to simulate electrical discharges. It has been combined with the finite element method, aiming to make it capable to handle arbitrary geometries. There are several possible further improvements for POSS that can be done. First, second order shape functions can be used in finite element formulation of POSS to reduce the unknowns. Second, the problem of mass-conservation requires a rigorous discussion from the mathematic point of view. Third, the efficiency of interpolation can be further improved in later studies.

**Paper IV** proposed an efficient model for glow corona discharges which can predict the self-oscillations in current produced by positive glows. Several experiments in air and at atmospheric pressure are used as benchmarks to verify the model. Even though the assumptions used in the model are independent of the gas medium and gas pressure, the comparison between simulations with available experiments under other conditions (different gas and pressure) in the literature is required. Moreover, the simplest fluid model is used in **Paper IV,** which means that all the positive ions have the same mobility and reaction rates with other species. The next step is to use a fluid model with a more elaborated kinetic scheme as in **Paper V** to further investigate the kinetic dynamics of glow corona discharges. In addition, the humidity effect on the glow corona discharges can be assessed in the future.

In **Paper V**, the dynamics of the streamer-to-leader transition is evaluated for two discharge events in a 1 m rod-plate gap. In the future, the model can be used to investigate the charge dynamics of such a transition in a general case, for example, to calculate the injected charge required to initialize leaders in nature. In **Paper V**, it is suggested that humidity plays an important role in the avalanche-to-streamer transition which was poorly understood. The next step is thus to perform the simulation of streamer filaments with a detailed kinetic scheme as proposed in **Paper V**.

Since electrons can be considered, the model proposed in **Paper IV** can be applied in the future for other applications where the widely used Kaptzov's approximation may not hold. For instance, in hybrid UHV AC/DC transmission lines, the space charge injected into the space is not monopolar and thus it is not straightforward to apply Kaptzov's approximation.

In **Paper VI** and **Paper VII**, the simulations of glow-to-streamer transition were conducted for scaled configurations. The next step is to perform simulations for real cases with the efficient model proposed in **Paper IV**. For example, both shielding lines and phase lines can be simulated together in a 2D Cartesian coordinate system. In this way, the space charges injected from those conductors are coupled together and a more complete evaluation of the glow-to-streamer transition can be performed.

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