Fundamental Investigation of Dry EDM Plasmas

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FUNDAMENTAL INVESTIGATION OF DRY EDM PLASMAS

A THESIS SUBMITTED TO ATTAIN THE DEGREE OF

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(DR. SC. ETH ZURICH)

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2018
I dedicate this dissertation to Erica Arruda Malaspina, love of my life.
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### Acronyms

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<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AFM</td>
<td>Atomic force microscopy</td>
</tr>
<tr>
<td>CERN</td>
<td>European Organization for Nuclear Research</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal-oxide semiconductor</td>
</tr>
<tr>
<td>CR</td>
<td>Collisional-radiative</td>
</tr>
<tr>
<td>DC</td>
<td>Direct-current</td>
</tr>
<tr>
<td>DEDM</td>
<td>Dry electrical discharge machining</td>
</tr>
<tr>
<td>EDM</td>
<td>Electrical discharge machining</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width of a half maximum</td>
</tr>
<tr>
<td>HAVA</td>
<td>Hot anode vacuum arc</td>
</tr>
<tr>
<td>IWF</td>
<td>Institute of Machine Tools and Manufacturing</td>
</tr>
<tr>
<td>LTE</td>
<td>Local thermodynamic equilibrium</td>
</tr>
<tr>
<td>MEMs</td>
<td>Microelectromechanical systems</td>
</tr>
<tr>
<td>MRR</td>
<td>Material removal rate</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>OES</td>
<td>Optical emission spectroscopy</td>
</tr>
<tr>
<td>PIC/MCC</td>
<td>Particle in cell/Monte Carlo collision</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>SAEM</td>
<td>Spark assisted electrochemical machining</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>WEDM</td>
<td>Wire electrical discharge machining</td>
</tr>
<tr>
<td>µ-EDM</td>
<td>Micro electrical discharge machining</td>
</tr>
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</table>

### Latin symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Probability of state transition</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Atomic transmission coefficient or Einstein coefficient</td>
</tr>
<tr>
<td>$A_{qp}$</td>
<td>Spontaneous emission</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Radiating surface area of the plasma</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>Al I</td>
<td>Optical emission line of neutral aluminium</td>
</tr>
<tr>
<td>Al II</td>
<td>Optical emission line of singly ionized aluminium atom</td>
</tr>
<tr>
<td>Al III</td>
<td>Optical emission line of doubly ionized aluminium atom</td>
</tr>
<tr>
<td>Al IV</td>
<td>Optical emission line of triply ionized aluminium atom</td>
</tr>
<tr>
<td>Alfr</td>
<td>Fraction of aluminium composition of the plasma</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>Bpq</td>
<td>Stimulated absorption</td>
</tr>
<tr>
<td>Bqp</td>
<td>Stimulated emission</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
</tr>
<tr>
<td>Cpq</td>
<td>Collisional excitation</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>Cu I</td>
<td>Optical emission line of neutral copper</td>
</tr>
<tr>
<td>Cz</td>
<td>Sum of rates of possible radiative and collisional transitions</td>
</tr>
<tr>
<td>Cufr</td>
<td>Fraction of copper composition of the plasma</td>
</tr>
<tr>
<td>d</td>
<td>Gap size</td>
</tr>
<tr>
<td>Dpq</td>
<td>Collisional deexcitation</td>
</tr>
<tr>
<td>e</td>
<td>Elementary charge</td>
</tr>
<tr>
<td>E</td>
<td>Electric field</td>
</tr>
<tr>
<td>EL</td>
<td>Electron energy level</td>
</tr>
<tr>
<td>g</td>
<td>Statistical weight of the excited level</td>
</tr>
<tr>
<td>G</td>
<td>Electric discharge arc conductance</td>
</tr>
<tr>
<td>G0</td>
<td>Minimum plasma conductance</td>
</tr>
<tr>
<td>G1</td>
<td>Arc conductance given by Cassie equation</td>
</tr>
<tr>
<td>G2</td>
<td>Arc conductance given by Mayr equation</td>
</tr>
<tr>
<td>Gt</td>
<td>Total plasma conductance</td>
</tr>
<tr>
<td>h</td>
<td>Planck constant</td>
</tr>
<tr>
<td>hi</td>
<td>Heat transfer coefficient</td>
</tr>
<tr>
<td>H</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>Hfr</td>
<td>Fraction of hydrogen composition of the plasma</td>
</tr>
<tr>
<td>Ha</td>
<td>Optical emission line of neutral hydrogen $\alpha$</td>
</tr>
<tr>
<td>Hb</td>
<td>Optical emission line of neutral hydrogen $\beta$</td>
</tr>
<tr>
<td>i</td>
<td>Simulated arc current</td>
</tr>
<tr>
<td>ie</td>
<td>Stagnation enthalpy of the plasma outside the sheath</td>
</tr>
</tbody>
</table>
\( i_w \quad m^2 s^{-2} \) Enthalpy of the plasma near the electrode surface
\( I \quad A \) Electric current
\( I_L \quad cd \) Light intensity
\( I_{pq} \quad s^{-1} \) Beam and non-thermal electron collisions
\( I_R \quad \text{a.u.} \) Relative optical emission line intensity
\( j_e \quad A \cdot m^{-2} \) Electron current density
\( \bar{J} \quad - \) Frequency-averaged mean intensity
\( k \quad - \) Integer position indexes for radial intensity
\( k_B \quad eV \cdot K^{-1} \) Boltzmann’s constant
\( L \quad W \cdot sr^{-1} \cdot m^{-2} \) Radiance
\( L_\lambda \quad W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1} \) Spectral radiance
\( n_z \quad cm^{-3} \) Density of species of charge \( z \)
\( N \quad cm^{-3} \) Density of neutral particles
\( N_e \quad cm^{-3} \) Density of electrons
\( N_L \quad - \) Number of energy levels
\( N_z \quad - \) Number of plasma zones with constant emission coefficient
\( N_2 \quad - \) Molecular nitrogen
\( p \quad Torr \) Gas pressure in the gap
\( P_0 \quad W \) Constant power dissipation by conduction
\( q_a \quad W \) Heat flux from a thermal plasma to the anode surface
\( q_c \quad W \) Heat flux by conduction
\( q_{conv} \quad W \) Heat flux by convection
\( q_j \quad W \) Thermal and kinetic energy of electrons that penetrate the anode surface
\( q_r \quad W \) Radiative heat flux
\( q_{ra} \quad W \) Radiative heat transfer from the plasma to the anode surface
\( q_{re} \quad W \) Radiation of a hot spot
\( q_v \quad W \) Anode material vaporization energy
\( q_{\phi a} \quad W \) Heat flux generated by condensation of electrons at the anode surface
\( R \quad \Omega \) Resistance
\( S_\lambda \quad W \cdot sr^{-1} \cdot m^2 \) Source function
\( t \quad \mu s \) Electric discharge pulse duration
**Greek symbols**

- $\alpha$ - Fraction of electric current
- $\alpha_{qp}$ $s^{-1} \cdot cm^{-3}$ - Radiative recombination of an ion
- $\beta_{pq}$ $s^{-1}$ - Photoionization plus stimulated recombination
- $\gamma_{pq}$ $s^{-1} \cdot cm^{-3}$ - Collisional ionization
- $\Gamma$ - Coupling parameter
- $\Gamma_z$ $s^{-1} \cdot cm^{-3}$ - External flux by diffusion and convection of ions of charge $z$
- $\Delta \lambda_W$ $nm$ - Full width of a half maximum
- $\Delta s_i$ $\mu m$ - Thickness of a plasma zone with constant emission coefficient
- $\varepsilon$ $W \cdot sr^{-1}$ - Emission coefficient
- $\varepsilon_\lambda$ $W \cdot sr^{-1}$ - Emission from a plasma slab
- $\delta_{qp}$ $s^{-1} \cdot cm^{-6}$ - Collisional recombination
- $\theta_1$ $\mu s$ - Time constant of Cassie equation
- $\theta_2$ $\mu s$ - Time constant of Mayr equation
- $\kappa$ $m^{-2}$ - Wavelength-dependent absorption coefficient
- $\kappa_{qp}$ $s^{-1} \cdot cm^{-3}$ - Electron capture
- $\lambda$ $nm$ - Wavelength
- $\sigma$ $kg \cdot s^{-3} K^{-4}$ - Stefan-Boltzmann constant
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{pq}$</td>
<td>$s^{-1}$</td>
<td>Autoionization</td>
</tr>
<tr>
<td>$\phi_a$</td>
<td>$eV$</td>
<td>Work function</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$s^{-1}$</td>
<td>Wave frequency</td>
</tr>
<tr>
<td>$\tau$</td>
<td>-</td>
<td>Optical depth</td>
</tr>
</tbody>
</table>

Dry electrical discharge machining (DEDM) has been developed as an alternative manufacturing process to the traditional EDM in oil dielectric. The absence of liquid dielectric allows DEDM to be performed by simpler and environmentally friendlier machines. The erosion in DEDM mainly occurs due to the bombardment of the workpiece material by charged particles produced by micro electric discharges. Therefore, understanding of the fundamental properties of micro discharge plasmas is necessary in order to explain the erosion mechanisms in this process. The present work introduces well-established methods from the field of plasma physics as effective tools to analyse DEDM plasmas and their interactions with the electrode material. Advanced interpretation of optical emission spectroscopy supported by a commercial collisional-radiative (CR) model gives a new insight into the complex DEDM micro discharges. Emission spectra simulations indicate that the studied DEDM plasmas must either have an electron temperature profile peaking at the plasma centre or an electron beam formed within the discharge. In addition, the discharges performed with a point-type cathode are similar to hot anode vacuum arcs (HAVA) with plasma properties compatible with the formation of a hot anode spot. The properties of a HAVA, with inert cathode and active anode, can explain the very small tool electrode wear obtained in DEDM. Moreover, DEDM discharges are mainly formed of metal vapour originated from the electrodes. In contrast, discharges in oil are dominated by components of the dielectric with just little metallic contamination. Finally, the anode power deposition in DEDM is calculated in the present work by a thermal plasma model supported by emission spectra simulations and by electrical circuit simulations with a modified Cassie-Mayr model. This investigation shows that most of the discharge power, between 80% and 90%, is deposited onto the anode material.

Keywords
Dry electrical discharge machining, micro discharge plasmas, optical emission spectroscopy, emission spectra simulations, discharge power deposition.

Schlüsselwörter

Trockene Funkenerosion, Mikroentladungsplasmen, optische Emissionsspektroskopie, Simulation von Emissionsspektren, Funkenergieeintrag.
1. **INTRODUCTION**

Electrical discharge machining (EDM) is one of the most widely applied non-conventional machining processes. EDM is normally dedicated to the production of workpieces made of difficult-to-machine materials with complex geometries. The main focus of the EDM market is on the production of injection molds and dies for several industrial areas, such as aerospace, medical device, automotive and electronic components. In addition, different types of EDM processes have been developed for distinct applications, such as die-sinking, wire, milling and drilling-EDM.

The material removal in EDM results from the thermal erosion of the workpiece material by electric discharges, as presented in Fig. 1.1. The discharge plasmas create craters on the workpiece, shaping its surface. Independent of its hardness, any material that conducts electricity can be machined by EDM. The material removal occurs in the gap between the tool and workpiece, which is normally filled with a liquid dielectric medium.

![Electric discharge machining process](image)

*Fig. 1.1: Electric discharge machining process [45]*

The dielectric medium isolates the electrodes and solidifies the removed molten material into small spherical particles, which are flushed out of the erosion gap. However, oil-based dielectric media, which are mostly adopted for die-sinking EDM applications, generate toxic gases and non-environmentally friendly waste during the machining process, as explained by Leão et al. [71].

Dry electrical discharge machining (DEDM) has been presented as an environmentally friendlier alternative to the conventional die-sinking EDM process in oil. DEDM works with gases instead of liquid dielectric media. Therefore, simpler machines can perform DEDM due to the absence of liquid dielectric. Milling and wire-DEDM are some of the variations of this process, which are shown in Fig. 1.2.

DEDM was reported for the first time in 1985 by the National Aeronautics and Space Administration (NASA) [105], where this process was performed with argon and helium as dielectric media. Later, Kunieda et al. [69] presented the feasibility of DEDM in air and oxygen as dielectric. According to their results, less tool wear and higher material removal rates (MRR)
are observed when this process is performed with a cathode tool. Kunieda et al. [66] summarizes the following DEDM characteristics:

- MRR can reach values substantially higher than EDM in oil, if oxygen is used as dielectric;
- Very small tool electrode wear is observed for any pulse duration;
- Very thin white layer and small number of micro cracks are formed on the workpiece surface;
- Small forces actuate during the DEDM process, when compared with EDM in liquid;
- Erosion gap considerably smaller than in conventional EDM;
- No corrosion of the workpiece, which commonly occurs in deionized water.

DEDM is usually performed with a thin-walled pipe tool cathode, in which a high-pressure gas is flushed. According to Kunieda et al. [67], 3D milling-DEDM performed with oxygen as dielectric can achieve MRR around 5 times higher than the same process in oil. These authors infer that the 3D milling-DEDM works under a controlled “quasi-explosion mode”. Strong heat is generated under this working mode due to thermally activated chemical reactions between the eroded material and oxygen, which leads to explosive melting and evaporation. Similar results were reported by ZhanBo et al. [138] for 3D milling-DEDM of cemented carbide, who indicate the same material removal mechanism described by Kunieda et al. [5].

Roth et al. [110] infer that the presence of oxygen in the gap also leads to a better stability of the machining process. Oxidation of the material of the debris removed from the crater drastically decreases their electrical conductivity, resulting in a reduction of short circuit occurrence during the erosion process. Furthermore, a substantial drop in the reattachment of debris to the workpiece surface is reported when oxygen is flushed into the gap, which is also attributed to the debris surface oxidation according to Roth et al. [19]. Later, Uhlmann et al. [130] presented benefits of gas injection under high pressure into the erosion gap for machining of micro holes. Their results suggest that the strong gas flow efficiently removes debris from the gap thanks to the low dielectric viscosity.

Different technologies have been developed during the last years in order to improve and support the DEDM process, in particular hybrid processes. Due to the small dimension of the DEDM gap, which can easily lead to undesirable short circuit during the machining process, the gap control is particularly important in this process. Therefore, Kunieda et al. [68] applied piezoelectric actuators in DEDM to provide a better frequency response of the erosion gap control. Their results show that the stabilization of the gap by the piezoelectric servo system leads to larger MRR. Zhang et al. [139] presented ultrasonic-assisted DEDM as a new technology to increase MRR. Joshi et al. [51] developed a DEDM process assisted by pulsating magnetic fields, which presented increase in MRR and improvements in eroded surface quality. Shen et al. [114] showed large energy levels, long discharge pulses, gaseous dielectric flushing under high pressure and high tool electrode rotation as a combination that significantly increases MRR in DEDM. Moreover, Tao [122] has published several
investigations reporting that gas-liquid mixtures can lead to higher MRR and better surface qualities.

![Fig. 1.2: (a) Milling-DEDM [67]; (b) Wire-DEDM [54]](image)

Although the EDM process exists for more than 60 years, the physics of its electric discharges in liquid or gaseous dielectric is not well understood yet. Due to this reason, optimization of the EDM process is still based on empirical methods and recipes. Further development of the EDM technology depends on the elucidation of its physical phenomena, since understanding of plasma-material interactions is necessary in order to explain the tool and workpiece electrode erosion mechanisms. Moreover, electric discharges can be generated from different breakdown mechanisms, which depend on the applied open voltage, erosion gap, dielectric medium, material and geometry of the electrodes.

EDM discharges are formed in micrometre gaps. This makes the discharge plasma diagnostics very challenging. Optical emission spectroscopy, high-speed imaging and electrical parameter measurements are some of the very few methods capable to provide information on the EDM plasmas. Optical emission spectroscopy of EDM plasmas has been applied by several researchers for over 20 years. The EDM plasma properties commonly analysed are the electron temperature and density. The electron temperature is calculated by the two-line Boltzmann method, assuming discharges in local thermodynamic equilibrium (LTE), whereas the electron density is estimated from the H\textalpha line broadening given by the Stark effect. However, the outcomes of these methods do not provide a detailed description of the EDM plasmas and their interactions with the electrode material.

The aim of the present work is the introduction of well-established models, theories and methods from the field of plasma physics as tools to support advanced diagnostics of the DEDM plasmas and their interactions with the electrodes. Application of modern optical equipment together with numerical simulations gives a new insight into the physics of DEDM plasmas. Interpretation of optical emission spectroscopy of DEDM discharges supported by collisional-radiative numerical simulations allows estimating several important plasma parameters, such as electron temperature and density profiles, distribution of ionic species and plasma composition. Even discharges which are not in thermodynamic equilibrium can be
analysed by the advanced plasma diagnostics proposed here. Furthermore, DEDM discharge energy balance is determined by a thermal plasma model and electrical circuit simulations.

The methods proposed in the present work are able to provide important plasma information for improvements of the DEDM process, whereas perspectives for advanced plasma diagnostics are opened for EDM processes in general, as well as the design of new electric discharge generators. In addition, even beyond EDM applications, the proposed methods allow estimating micro discharge plasma properties present in accelerators, mini thrusters, relays and several different manufacturing processes that have plasma-material interactions as a working principle.
In the present chapter, the state of the art of electric discharges in inter-electrode gaps and plasma diagnostics is presented. In addition, physical models used to estimate the electric discharge energy deposition onto the electrode material are also introduced.

2. **State of the Art**

2.1. **Electrical breakdown**

**2.1.1. Electrical breakdown in dielectric media**

Electrical breakdown is the term used to name the physical process that leads to the creation of an electric discharge. Since EDM discharges start from an electrical breakdown in an inter-electrode gap filled with a dielectric medium, understanding about the breakdown mechanisms is necessary in order to explain the physics involved in this machining process. In EDM, the tool moves towards the workpiece with an applied open voltage, usually between 50 and 250 V. The high electric fields formed due to the small gap between electrodes, which normally varies from 10 to 100 µm, lead to the dielectric breakdown. The electric field can be increased by the presence of micro protrusions on the electrode surface, sharp edges and small metallic particles present in the gap.

The breakdown properties in EDM can strongly depend on the applied electrical parameter set, electrode material, electrode geometry, dielectric medium and inter-electrode gap dimension. The ionization of the dielectric medium, resulting from the electrical breakdown, leads to a rising electric current $I$ and an abrupt decrease in the voltage when the plasma is formed. The voltage observed during the electric discharge is named discharge voltage or burning voltage $U_e$.

One of the first investigations about the electrical breakdown in gaseous dielectric was reported by Paschen in 1889 [24, 59, 87, 91]. The Paschen’s law calculates the breakdown voltage as a function of the product of the gap size $d$ and the gas pressure in the gap $p$. According to this law, the breakdown voltage decreases if the product $p \cdot d$ becomes smaller; however, below a critical value of $p \cdot d$, the breakdown voltage starts to increase. The reason for this breakdown voltage increase is the small amount of dielectric medium in the gap, which does not allow the necessary particle collisions to build up an electron avalanche. Typical U-shaped curves, obtained from the Paschen’s law, are presented in Fig. 2.1.

Townsend published a theory in 1900 concerning the physics of the pre-breakdown in gaseous dielectric. This theory assumes the multiplication of electron avalanches via secondary cathode emission, which results from collisions between electrons and gas molecules. These collisions generate ions and electrons in a self-maintaining mechanism, as described by Braithwaite [16]. The Townsend’s theory is valid for $p \cdot d < 4,000 \text{ Torr} \cdot \text{cm}$ in
air as dielectric. In 1953, Loeb and Meek proposed the widely accepted streamer theory, which is valid for $p \cdot d \geq 4,000 \text{Torr} \cdot \text{cm}$. According to this theory, sparks are originated from the growth of a weakly ionized channel starting from the cathode, called “streamer”, as presented by Raizer [103].

![Experimental Paschen curves for electric discharges between copper electrodes in argon as dielectric medium with different inter-electrode gaps](image)

Fig. 2.1: Experimental Paschen curves for electric discharges between copper electrodes in argon as dielectric medium with different inter-electrode gaps [91]

The streamer is formed from a primary electron avalanche, which grows from the cathode towards the anode, as presented in Fig. 2.2a. In inter-electrode gap sizes up to a few centimetres, the streamer grows back from the anode towards the cathode after electron avalanches reach the anode. In this particular case, the streamer is called “positive streamer”. The electric discharge is formed when the positive streamer has contact with both anode and cathode electrodes, as schematically shown in Fig. 2.2b. The physics involved in the transition streamer-to-spark is still poorly understood. This transition probably occurs due to a “back streamer”, similarly to a “return stroke”, well-known from lightning discharges. Electric discharges in inter-electrode gap sizes larger than several tens of centimetres are triggered by a “negative streamer”, which is created by a different mechanism, as summarized in detail by Raizer [103].

The electrical breakdown mechanism in liquid dielectric media, present in the traditional EDM process, has different interpretations which have been presented by several authors. An investigation published by Beroual et al. [11] suggests that a positive streamer can be formed in the bulk liquid. This hypothesis is supported by high-speed imaging reported by Schulze et al. [112], who infer that the breakdown directly starts from streamers or micro-discharges in bulk oil or deionized water in micrometre gaps. Controversially, other publications [2, 63, 100] infer that the breakdown does not happen without the previous existence of gas bubbles in liquid dielectric. Currently, there is no scientific consensus about the development of streamers in the bulk liquid or in relation with the formation of gas bubbles, as summarized by Kolb et al. [62].
A different electrical breakdown mechanism has been reported for electric discharges in gaps smaller than 5 \( \mu m \) filled with gas. An investigation published by Radmilović-Radjenović et al. [101] presents experimental results, validated by an one-dimensional particle in cell/Monte Carlo collision simulation (PIC/MCC), which indicate that the breakdown across the small gap can happen at voltages far below the minimum predicted by Paschen’s curve. In addition, Takahito et al. [119] show that the electrical breakdown takes place apart from gas pressure in the small gap, suggesting that Paschen’s law is not valid under these referred conditions. Experiments reported by Torres et al. [126] indicate a linear dependence between the breakdown voltage and the size of the inter-electrode gap, as shown in Fig. 2.3.

This type of breakdown occurs in gaps considerably smaller than the ones calculated by the Paschen’s law, as registered for different gases by several authors [18, 24, 126, 127]. Radmilović-Radjenović et al. [102] explain that the reason for deviations from the Paschen’s
law in micrometre gaps is a mechanism similar to a vacuum breakdown. This particular electrical breakdown mechanism is the one mostly present in DEDM due to the typically adopted processing conditions.

**2.1.2. Vacuum breakdown mechanism**

The vacuum breakdown normally starts from a mechanism named field emission, as explained by Boxman et al. [14]. Electrons are extracted from the cathode due to the presence of a sufficiently strong electric field, which can be influenced by the cathode geometry. A point-type cathode or “whisker-like” protrusions on a flat cathode surface improve the necessary conditions for the occurrence of a vacuum breakdown.

In particular, vacuum breakdown in micrometre gaps is formed due to ion-enhanced field emissions, as explained by Radmilović-Radjenović et al. [102]. The breakdown takes place due to the high electric fields formed in the gap, combined with lowering of the potential barrier seen by the electrons in the cathode as ions approach. Thus, the electron emission process depends primarily on the electric field rather than on the relation between the electric field and the density of neutral particles in the gap ($E/N$). The vacuum breakdown mechanism in DEDM was for the first time reported by Roth et al. [109].

Timko et al. [124] describe that the vacuum breakdown starts in the gap with the ejection of particles from the electrode material due to its bombardment by electrons accelerated by the electric field. This process, named “sputtering”, leads to the formation of an increasing metal vapour within the gap. Simultaneously, a small amount of ions is formed, which quickly leave the gap due to the electric field. An avalanche of ionization begins when the metal vapour reaches a critical density value. This occurs because the mean-free path of the electron impact ionization becomes smaller than the gap between the electrodes. Strong ion flux is formed afterwards, resulting in further sputtering and electrode material evaporation. The coupled phenomena of sputtering, ionization, ion flux and erosion are the sustaining mechanism of the discharge.

**2.2. Electric discharge plasmas**

Electric discharge is the passage of an electric current through a medium after the occurrence of an electrical breakdown. The medium in which the electric current flows is initially an insulator, which becomes conductive due to the breakdown. Furthermore, the electric current is conducted by charged particles of the formed plasma in response to an applied electric field or pressure gradient, as explained by Hantzsche [39]. Nakanishi [92] infers that the plasma of a gas discharge is initially formed when the energy received by molecules of a gas is stronger than the bond between their component atoms, which leads to molecules dissociation into single atoms. In a second stage, the energy received by single atoms overcomes their ionization potential, when orbital electrons ionize. In general, the conductivity of the plasma increases with the electron temperature and the plasma can be assumed to be a low
resistance current conductor. In particular, vacuum discharge plasmas are mainly composed of material from the electrodes. This type of discharge can be categorized by its main source of metallic components, as described by Boxman et al. [14].

Several different discharge types have been intensively investigated over the last century for different applications. Electric discharges in dielectric media consist in steady or transient-state processes and can be classified according to their current and voltage properties, as reported by several authors [16, 75, 103, 124]. There are four main categories of steady or quasi-steady-state processes in electric discharges which depend on the electric current, as summarized in the following topics and illustrated in Fig. 2.4. Unlikely, the spark discharge is a transient phenomenon.

![Electric discharges diagram with currents as abscissae and voltages as ordinates](103)

- **Townsend’s dark discharge**: consists in a gaseous ionization phenomenon by ion impacts on the cold cathode;
- **Glow discharge**: generates weakly-ionized plasma in non-equilibrium state. This kind of discharge is visible as an uniform glowing column;
- **Corona discharge**: is normally formed by strongly non-uniform electric fields in specific electrode surface regions, such as protrusions and sharp edges;
- **Arc discharge**: has a thermionic process as electron emission mechanism. This discharge is generated by cathode heating and typically presents bright light emission. Normally, the plasma of arc discharges generated in atmospheric pressure can be assumed to be in thermodynamic equilibrium.

Kunze [70] explains that the thermodynamic equilibrium takes place when the plasma is in a closed system and its processes occur based on the principle of “detailed balance”.

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**Fig. 2.4: Electric discharges diagram with currents as abscissae and voltages as ordinates [103]**
According to this principle, every atomic process has its inverse with equal rates in both directions. The principle of detailed balance is disturbed when deviations from the plasma equilibrium occur; however, if the equilibrium is locally preserved, the plasma can be considered in local thermodynamic equilibrium (LTE). The electron energy distribution of a plasma in LTE corresponds to a classical Maxwell-Boltzmann distribution. The plasma is not in thermodynamic equilibrium when a fraction of its electrons is highly accelerated (high-energy electrons) in comparison with its atoms and ions.

The properties of electric discharges can be significantly affected by an imposed magnetic field due to its influence on the motion of the plasma particles. Since a magnetic field is generated by the discharge current flow, the coupling between this formed magnetic field and the electron distribution within the plasma can substantially change the electric discharge characteristics. The imposition of a magnetic field $B$ with a component perpendicular to the electric field $E$ leads to an electric current component that is perpendicular to $B$ and $E$. This phenomenon is named Hall Effect and is commonly found in vacuum discharges. Furthermore, the magnetic field induced by the electric current flow leads to an additional effect, which is the magnetic constriction of the mass flow. The occurrence of this effect depends on the radial distance from the plasma central axis, assuming a constant electric current density.

The above-mentioned physical phenomena, concerning mass flow and Hall effect, cause a geometrical constriction of the energy flux to the anode and are associated with the formation of a hot spot in vacuum discharges, as described by Boxman et al. [14].

### 2.2.1. Electric discharge plasmas in micrometre gaps

Many similarities exist between electric discharges in millimetre gaps and discharges in micrometre gaps, such as the EDM ones. However, there are significant differences between them due to the volume of dielectric in the gap and electrical parameters, as explained by Toyota et al. [127]. Knowledge about the physics of the electric discharges in micrometre gaps is of fundamental importance for the development of several current industrial applications, such as microelectromechanical systems (MEMs), micro plasma reactors and other electrical devices with micrometre separations. Furthermore, the physics involved in discharge plasmas in micrometre gaps is also present in several natural phenomena. The so-called weakly-coupled regimes, as found in some micro plasmas, are of high interest for basic plasma physics, since such particular plasmas are also found in stars and other high electron density objects, as described by Fortov et al. [31].

There is only scarce information about micro plasmas in the literature, since the analysis of plasmas with space constraint environment and short duration is very challenging and demand modern measuring equipment, as shown by several authors [8, 18, 43, 58, 126, 131]. According to Hollenstein et al. [44], there is even less information regarding plasmas formed in sub-micrometre gaps. Most of the existing literature concerning analysis of micro electric discharges and their interactions with the electrode material has focus on the EDM
As mentioned in chapter 1, EDM plasmas have been investigated for many years by direct and indirect methods. High-speed imaging, electrical parameter measurements and optical emission spectroscopy (OES) are classical non-intrusive plasma diagnostics, which allow the analysis of plasmas formed in micrometre gaps.

The first investigation of EDM plasmas by OES was conducted by Albinski et al. in 1995 [3]. Later, Natsu et al. [93] studied micro plasma temperature distributions, applying spatially-resolved OES together with the Abel inversion technique. Descoeudres [23] developed time and spatially-resolved OES of EDM plasmas in liquid dielectric media. His analysis shows that cold ($T_e = 8,000 \, K$) and dense ($N_e = 10^{18} \, cm^{-3}$) plasmas are formed in the erosion gap. These parameters indicate that EDM plasmas have weakly-coupled regimes, with coupling parameter $\Gamma$ varying from 0.3 to 0.45. The coupling parameter quantifies the “degree of ideality” of the plasma, according to which the plasma is called:

- Ideal if $\Gamma \ll 1$;
- Weakly non-ideal if $\Gamma \leq 1$;
- Strongly coupled if $\Gamma > 1$.

In addition, Descoeudres [23] infers that the electron density $N_e$ and the temperature $T_e$ of EDM plasmas in liquid do not change significantly by varying the applied electrical parameter set, electrode material, electrode polarity and composition of the dielectric. Later, Maradia et al. [84] validated electron density calculations of micro electric discharge plasmas in oil by a commercial collisional-radiative (CR) code, PrismSPECT [82]. The simulated emission spectra show that the $H\alpha$ spectral line is broadened and shifted with increasing electron density, which fits to the analysis of the experimental spectra. Other authors [61, 66, 90, 94, 106] have conducted investigations of discharges in micrometre gaps filled with liquid dielectric media since the last decade.

High-speed imaging and optical emission spectroscopy analyses of DEDM plasmas in micrometre gaps filled with gas at atmospheric pressure, using different materials and electric discharge parameter set, have been reported by a few authors [53, 61, 117, 118]. In contrast to results obtained for electric discharges in liquid dielectric media, micro plasmas in air have lower density of electrons, varying from $10^{12}$ to $10^{17} \, cm^{-3}$, whereas the plasma properties change substantially with the selected electrode material and electrical parameter set.

2.3. Plasma-material interactions

2.3.1. Electrode regions and arc modes

The behaviour of direct-current (DC) discharges depends on the phenomena involved in the electrode-plasma interface, which include emission of electrons and neutral atoms from the electrode material into the plasma. As described by Baalrud et al. [4], a non-neutral region is formed in the vicinity of the electrode surface, named sheath. Sheaths have a large potential
difference between the electrode and the bulk plasma, acting to balance the electrons and ions lost globally from the plasma. Ion sheaths reflect part of the incident electron current, whereas electron sheaths reflect part of the ion current. In addition, the sheath potential depends on the electrode current and its mechanisms of charged particles transportation.

In the cathode region, electrons are emitted from the electrode by different mechanisms. Hantzsche [39] infers that the cathode potential drop of low current discharges, which are sustained by secondary electron emissions, is connected with the current density. High electric currents lead to a contraction of the active part of the cathode, called cathode spot. The cathode spot is formed due to the ion flow from the plasma to the cathode surface. The ion flow causes heating by impact of accelerated ions in the cathode sheath, as well as a high electric field at the cathode region due to the space charge.

Cathode spots supply high electron current densities to the discharge, typically around $10^{11}$ A/m². Electrons can be emitted from the cathode spot by tunnelling (field electron emission), emission of high-energy electrons from a strongly heated metallic surface (thermionic emission), a combination of these two mechanisms (thermionic field emission), or non-stationary explosive emission of electrons and explosive evaporation of cathode material, named “thermal runaway”. The thermal runaway normally occurs due to a high concentration of thermal energy in a small region of the cathode surface, such as protrusions, as described by Boxman et al. [14].

In the anode region, a steep gradient of atom density near the anode is formed due to its sputtering by the electron flux. Emission of atoms from the anode surface takes place mainly by evaporation and sublimation due to interactions of the electrode material with the discharge plasma. Since the sputtered atoms leave the anode surface with low velocity, most of them are ionized by the electron flux, as explained by Afanas’ev et al. [1]. Li et al. [72] infer that a large energy is absorbed by the anode in DEDM, so knowledge about the anode region is crucial to understand the physics of the discharges in this manufacturing process. Boxman et al. [14] introduce different anode modes of vacuum discharges, which are presented in Fig. 2.5 as a function of the arc current and inter-electrode gap size, as well as described in the following topics:

- Diffuse arc mode: is formed under low electric currents ($< 1 \text{kA}$) and can be subdivided in two types of discharge. In its first mode, the anode is an inert electrode, which collects the flux of particles emitted from the cathode. In its second mode, which is more common, the anode emits particles due to sputtering of the electrode material. The cathode phenomena control the behaviour of the vacuum arc in the both mentioned types of discharge. Most of the sputtered atoms of the anode material are ionized by the electron flux near the anode surface. Material erosion of both cathode and anode is very low in this arc mode;

- Footpoint mode: is formed under intermediate electric currents (up to a few kA) with little activity of the anode in the discharge, whereas the inter-electrode gap is filled with a bright diffuse glow. Single or several small bright spots are formed on the anode
surface, which are named footpoints. The formation of footpoints is associated with the anode melting and the presence of considerable anode material composition in the discharge plasma. Erosion of the electrodes is small and normally larger on the anode side;

- Anode spot mode: is formed under high electric currents (tens of kA) with a very active anode, which suffers severe erosion. An arc column is formed in the inter-electrode gap, while one large or several small spots cover the electrodes. The anode spots have a temperature near the atmospheric boiling point of the electrode material, which is substantially higher than the anode spot temperatures observed in the footpoint mode. Large amount of atoms evaporated from the anode are ionized, probably near the electrode surface, and emitted by the anode spots;

- Intense arc mode: similar to the anode spot mode, this arc is formed in smaller gaps under high electric currents (tens of kA) with a very active anode. The plasma is very bright and covers both electrodes, filling the inter-electrode gap. The intensity and frequency of the arc voltage are low, when compared with the voltage of anode spot mode arcs, but still higher than in the low current diffuse mode. Furthermore, an anode jet extending to the cathode occurs in this type of discharge and both electrodes are severely eroded.

![Diagram of anode discharge modes](image)

Fig. 2.5: Anode discharge modes [14]

The above-cited anode modes refer to traditional vacuum arcs, which are formed with high total discharge power. Dorodnov et al. [27] reported for the first time a vacuum discharge performed with moderate arc power, named hot anode vacuum arc (HAVA). Katsch et al. [55] show that a HAVA can be generated with \( I = 25 \, A \) and \( U_e = 17 \, V \) between aluminium electrodes, once the anode material is thermally isolated from its surroundings. A HAVA normally starts as a diffuse arc, burning in the cathode material. The diffuse arc mode changes
to a HAVA during the development of the discharge, in which the anode actively takes part due to the formation of a hot anode spot.

As explained by Miller [88], the energy of atoms and ions emitted from the anode in a HAVA is considerably low, when compared with a similar cathodic vacuum arc. Negligible cathode sputtering occurs, whereas its surface is coated by anode material during the discharge. In addition, although the cathode is a source of electrons to the discharge, the cathode drop is much less than in other vacuum arcs and much of the energy that sustains the arc is provided by the anode and the inter-electrode plasma. Thus, the plasma composition of a HAVA is dominated by the anode material with just little or even no cathode material contribution.

2.3.2. Electrode erosion

Understanding of the physics involved in the plasma-material interactions requires knowledge in different areas, such as chemistry, plasma physics and materials science. The electrode erosion occurs due to a high rate of energy transfer from the plasma to the electrode material. Moving radially from the central axis of a thermal plasma column, in direction to its “edge”, a decrease in electron temperature and density takes place, changing conditions for the electrical current flow, as reported by different researchers [21, 22, 108]. During the electric discharge, the energy is mainly transferred from the plasma to the anode and cathode material, the surrounding dielectric and dissipated by radiation, as explained by Tariq et al. [123].

Craters made by short pulsed discharges in liquid, of around 5 μs, are mostly generated by evaporation of electrode material, while part of the molten material is expelled by electrostatic forces, as described by Izquierdo et al. [48]. Furthermore, longer pulses lead to larger expansion of the plasma and to a reduction of the electrostatic forces, which distributes the electric discharge energy over a larger area. Singh et al. [115] infer that the electrostatic forces are much weaker for relatively long pulses, reducing their erosion effect to negligible values. The volume of material removed from the craters is larger for long pulses; however, the relation between the crater and resolidified layer volume is considerably smaller, which indicates an inefficient material ejection mechanism, as reported by Takezawa et al. [120].

Since the type of dielectric medium influences the discharge plasma properties, the crater left on the electrode material is also affected, as reported by Zhang et al. [141] and illustrated in Fig. 2.6. In the case of discharges in liquid dielectric, heating of the dielectric leads to its evaporation and the generation of a gas bubble around the plasma channel. The plasma channel expands completely in the micrometre gap in a few microseconds due to ionization of the surrounding formed gas. Furthermore, the plasma plume has dimensions considerably larger than the respective crater left on the electrode material, as reported by different authors [35, 57, 61]. The gas bubble also expands due to the pressure generated during the electrical breakdown, plasma radiation and kinetic energy, as proposed by Jahan et al. [49].
Fig. 2.6: Comparison of the external appearances of craters formed in (a) air; (b) kerosene; (c) deionized water; (d) emulsion; (e) oxygen. Pulse duration: 105 µs [141]

High-speed imaging of EDM discharges performed by Maradia et al. [85] shows the formation of gas bubbles and shock waves in-liquid and cloud build up in-mist dielectric media. The high-speed imaging measurements suggest strong hydrodynamic forces in the discharge region, which probably contribute to the electrode erosion. Later, Maradia et al. [84] reported high-speed imaging of discharges in oil, comparing gas bubble and plasma expansions in electric discharges with different anode and cathode materials. The impulse force given by the gas bubble dynamics has been calculated by Tohi et al. [125] through the Hopkinson bar method in electric discharges in liquid. The impulsive forces are estimated by this method from the measured displacement of two points on a metallic bar with known mechanical properties, where the EDM discharge is performed. Their experimental results fit well to the theoretical model proposed by Eckman et al. [29], which is based on the Navier-Stokes equation.

An investigation published by Izquierdo et al. [48] shows that the plasma overpressure prevents the electrode material boiling phenomenon in liquid dielectric. According to their research, right at the end of the discharge, the overpressure in the bubble disappears and part of the molten material is ejected from the crater region. Nevertheless, experimental results reported by other researchers lead to different conclusions concerning the material removal mechanism. High-speed imaging performed for electric discharges in oil have shown that material removal occurs while the bubble expands, whereas no debris is removed from the crater region after the end of the discharge and during the bubble contraction. A possible reason for the material removal during the discharge could be the pressure decrease during the bubble growth, inducing cavitation and degassing of the gaseous solution of the molten material, as inferred by different authors [41, 57].

Measurements of impulsive forces of single discharges performed by Tamura et al. [121] suggest that the expansion and contraction of the generated bubble in liquid dielectric and the shock waves produced by discharges in gas do not have relevant influence on the material removal. A more recent investigation, performed by Zhang et al. [140], contradicts these results, suggesting that the material removal is significantly affected by the magnitude of impulsive forces, guided by the inter-electrode gap distance. Later, Zhang et al. [141] confirmed these results regarding impulsive forces for discharges in gas, in which the impulsive forces play an important role as material removal mechanism, but contradicted them for discharges in liquid. Thus, so far there is no consensus about the effects of the impulsive forces on the material removal in EDM.
Beyond the understanding the physics of micro discharge plasmas, the development of new EDM technologies also depends on knowledge about the post-discharge, which is the stage after an electric discharge is extinguished. The research of post-discharges in large gaps filled with gaseous dielectric has been intensely developed for several years, mainly due to lighting source applications, as presented by Meek et al. [87]. However, the post-discharges in micrometre gaps have been analysed in just a few studies [23, 66, 84, 113], particularly concerning EDM.

High-speed imaging results, summarised by Schumacher [113], indicate that metallic particles ejected from the electrode material decrease the breakdown strength in the inter-electrode gap. Optical emission spectroscopy performed by Descoeudres [23] supports this thesis, indicating that the light emitted during the post-discharge is mainly from blackbody radiation. An investigation developed by Maradia [84] shows that relatively short pauses between two pulsed discharges can drastically change the optical emission spectra characteristics of the second discharge, as presented in Fig. 2.7. Further investigation is still necessary in order to explain the physics of the post-discharge in micrometre gaps, since the post-discharge plays an important role in the EDM process and has been just poorly researched up to now.

![Fig. 2.7: Time-resolved OES of EDM discharges in oil: (a) Long pause between electric discharges; (b) Short pause between electric discharges [84].](image)

### 2.3.3. Plasma-material interactions physical models

Plasma-material interactions have been investigated by experimental research and computer simulations. The physics of plasma-material interactions is governed by thermodynamics, plasma physics, chemistry, magnetohydrodynamics and fluid dynamics. Due to this complexity, many simplifications are necessary in order to develop non-prohibitive physical models.

Several discharge plasma channel simulation models have been presented in the literature. In 1951, Drabkina developed the first theoretical model of a spark channel between electrodes. This model considers an instantaneous plasma energy release, which generates a cylindrical region with pressure discontinuity and shock waves, as described by Freeman et al.
The Nordlund Group and the European Organization for Nuclear Research (CERN) [124] presented a molecular dynamics simulation of electrode erosion by discharge plasmas in vacuum, as shown in Fig. 2.8. Possible reasons for multiple appearances of complex craters made by single discharges in vacuum can be plasma density fluctuations and thermal spikes due to overlap of “showers” and clusters of charged particles during the movement of the anode and cathode spots, as reported in different investigations [26, 124]. Later, Yang et al. [135] proposed a molecular dynamics model to explain the material removal mechanism in micro-EDM (µ-EDM). Revaz et al. [107] developed a physical model that indicates the thermo-capillary (Marangoni) forces as the dominant plasma flushing effect in EDM.

Simulation of craters left on the electrode material by a single electric discharge, normally defined as a heat source, is one of the main focuses of EDM modelling. Simulation of single craters is the first step towards more sophisticated multiple-crater models, which could predict important EDM process outcomes such as MRR, tool electrode wear and workpiece roughness. However, the exact mechanism of electric discharge energy dissipation, which is an important crater model variable, is still disputed.

A few investigations about the energy distribution in EDM considering the physics of its discharges have been conducted. Magnetohydrodynamics simulations of steady-state DC discharges in air between parallel copper electrodes were proposed by Hayakawa et al. [40], as summarized by Kunieda et al. [66]. These simulations give indications on the electron temperature of the plasma. Furthermore, Hayakawa et al. [42] suggest that most of the discharge energy must be absorbed by the electrode material, while losses by convection and radiation are probably negligible. A theoretical model that calculates the proportion of energy transferred to the electrodes by single discharges was also proposed by Perez et al. [97]. This model is based on the electric current distribution, potential falls and thermophysical properties of the electrode materials. Heat transfer from single EDM discharges to the workpiece and tool is strongly affected by the properties and behaviour of the plasma adjacent to them; however, the above-cited publications do not consider the particular properties of the involved discharges due to the lack of detailed information regarding their plasma characteristics, such as dimension, composition, electron temperature and density.

Combinations of experimental analyses and simulation models have been proposed by several researchers in order to estimate the proportion of electric discharge energy transferred to workpiece and tool material in different EDM processes. In general, the energy transfer is determined indirectly by minimizing differences between heat transfer simulations and measurements of the electrode after the erosion process.
DiBitonto et al. [25] estimated an electric discharge energy fraction of about 18% to be absorbed by the cathode material in EDM performed in deionized water. This result was obtained by comparing simulations of a point heat source model and eroded surface measurements. Later, Patel et al. [96] developed a time-dependent heat transfer model. This model considers the heat flux onto the surface of the anode material given by an expanding Gaussian-distributed heat source. The fraction of energy transferred to the anode was estimated to be around 8%, assuming the same experimental conditions used by DiBitonto et al. [25]. Yeo et al. [136] calculated a discharge energy fraction distribution of 39% to the anode and 14% to the cathode in μ-EDM performed in oil. These calculations are based on correlations between electro-thermal modelling simulations and crater analyses. Similar approach was used by Zhang et al. [142], who additionally consider electric discharge plasma expansion, material removal and recast layer formation during the erosion process. The investigation developed by Zhang et al. [142] indicates that the energy absorbed by the workpiece material can vary from around 35% to 60%, depending on the adopted electrical parameter set and used dielectric medium.

Direct measurements of the electrode material temperature together with numerical simulations can also be used for estimating the electric discharge energy transferred to the anode and cathode material. Thermal response of single EDM discharges in oil was measured by Revaz et al. [108] with thermocouples and high resolution infrared thermography. According to their investigation, an energy fraction of 10% is estimated to be transferred to the workpiece electrode during the erosion process. This result is obtained from relations between temperature measurements and heat transfer numerical simulations. Later,
Zahiruddin et al. [137] calculated the power distribution in µ-EDM considering energy losses by heat conduction within the electrode material and energy carried by debris removed from the crater region. This investigation indicates that the energy distributed over anode and cathode must be between 10% and 15% of the total electric discharge energy, according to correlations between temperature measurements by thermocouples, material removal analysis and heat transfer simulations.
Currently, optimization of EDM processes is developed through empirical methods and recipes, since the physics of the electric discharges and the plasma-material interactions in micrometre gaps are poorly known. Understanding of the physics involved in the EDM discharge and its plasma properties could lead to a breakthrough in the development of new EDM processes and machines.

Only a few publications concerning DEDM plasma diagnostics are currently available in the literature. Thus, the physics involved in this type of plasmas is even less known than in EDM plasmas in liquid dielectric. Recent investigations indicate that DEDM discharges have some very particular characteristics, such as a vacuum breakdown mechanism and strong dependence of the plasma properties on the electrode material. Nevertheless, effects of the DEDM plasmas on the workpiece material removal and tool wear mechanisms have not been properly elucidated yet. Furthermore, some publications assume that DEDM produces gas discharge plasmas, similar to the ones created in EDM in liquid dielectric media; however, this assumption was never properly investigated.

In contrast to electric discharge plasmas in large gaps, which have been extensively investigated, discharges in micrometre gaps are still very poorly analysed. Micro discharge plasmas, such as the EDM one, are very difficult to diagnose due to their small dimensions and short duration. Only a few techniques can be used to analyse EDM plasmas, such as electrical parameter measurement (electric current and discharge voltage), high-speed imaging and optical emission spectroscopy. EDM plasma properties have been studied by optical emission spectroscopy for many years. However, only very limited information about the plasma, such as some estimation on electron temperature and density, can be directly obtained from the optical emission spectra.

Detailed information about the EDM plasma properties is crucial to understand its physics and to develop models that can simulate interactions of the discharge with the tool and workpiece material. Nevertheless, quantitative information concerning EDM plasma properties on the profiles of electron temperature and density, distribution of ionic species, electron energy distribution and fraction of different material components within the discharge are still lacking due to the limitations of the methods of analysis applied up to now.

Several simulation models have been developed in order to describe the physics of the material erosion in different EDM processes, most of them concerning simulations of crater formation by single discharges on the anode and cathode surfaces. Important simulation parameters, such as plasma heat source dimensions, discharge energy balance and dominant dissipation mechanisms are commonly assumed in those models. Since just limited information is available concerning the EDM plasma-material interactions, estimations of these parameters are usually based on crater analyses and iterative heat transfer simulations.
Currently, there is no analysis of the material erosion based on the EDM plasma properties, making those plasma-material interactions simulation models incomplete.

The global objective of the present work, which takes into consideration the above-mentioned research gaps, is a deeper insight into the physics of DEDM discharges. Thus, in order to characterize the DEDM plasmas, the following aspects must be considered, according to which this dissertation is structured:

- Since only a few parameters can be calculated directly from the optical emission spectra of the studied micro plasmas, more sophisticated analysis of optical emission spectroscopy results supported by a collisional-radiative model is needed in order to estimate several DEDM plasma properties. In the present work, the experimental setup and methods of analysis adopted for plasma diagnostics are reported in chapter 4 and a detailed analysis the DEDM plasma is presented in chapter 5;

- Analysis of DEDM plasmas under different processing conditions must be performed in order to characterize their effects on the physics of the discharges. Effects of the electrical parameter set, dielectric medium, electrode geometry, material and polarity on the discharge plasma properties are investigated in the present work and reported in chapter 6;

- An investigation of the discharge energy balance and its dissipation mechanisms is necessary in order to estimate the energy absorbed by the electrodes, since energy transfer from the discharge to the electrodes is an important parameter for the development of plasma-material simulation models of this process. The anode power deposition in DEDM is estimated by applying different methods in the present work, as reported in chapter 7. Finally, conclusions and outlook are given in chapter 8.

Part of the outcomes of the investigation reported in the referred chapters has been published in the form of articles in science journals and conference proceedings [77-81, 134].
The equipment used for electric discharge experiments, crater measurements and plasma diagnostics are described in the present chapter. Furthermore, the methods adopted for advanced plasma analysis are presented.

4.1. Electrical discharge machining equipment and setup

EDM experiments are done with a die-sinking Form 1000 AgieCharmilles EDM machine. This machine is adapted to perform single discharges for OES and high-speed imaging. The setup for single discharge experiments with the EDM machine is presented in Fig. 4.1.

![Electric discharge experimental setup](image)

Fig. 4.1: Electric discharge experimental setup

The discharges are performed by an ISO pulse generator, which drives the electric current during a pre-set pulse duration $t$. Specific electric current time behaviour can be set in the EDM machine, which is able to generate slope and square-shaped current pulses. Slope-shaped current pulses are normally adopted for die-sinking EDM in order to reduce the tool electrode wear, in particular when high electric currents ($I > 8 \, \text{A}$) are applied during the machining process, as described by Tsai et al. [128].

The electrical parameter set of the EDM machine also includes open voltage and electrode polarity. The movement of the electrodes is controlled by the servo motors of the EDM machine. Single discharges are generated by moving one electrode towards the other with an open voltage $U_{\text{open}}$ applied, since the discharge ignites when the electric field formed in the small electrode gap is high enough for the occurrence of the breakdown. The servomotor of the EDM machine automatically stops after the ignition.

Single discharge experiments are performed here with different dielectric media, electrode geometry configurations and electrical parameter set, whereas copper and aluminium are adopted as electrode material. In particular, aluminium is not commonly applied in EDM, neither as tool nor workpiece material. The selection of aluminium for the...
present investigation is particularly due to its well-known plasma emission spectra, which simplifies OES interpretation. Furthermore, although the main focus of this work lies on the investigation of DEDM plasmas, OES of discharges in oil is also performed. This is done in order to compare the plasma properties of discharges performed in very different dielectric media. OES and high-speed imaging of DEDM discharges are done in air at atmospheric pressure. Discharges in oil are performed in the EDM machine bath for OES, whereas high-speed imaging is done in a small bath, specially designed for this type of experiment.

The electric discharge experiments are drawn in point-to-point and point-to-plane electrode geometry configurations. The point-type electrodes are cylindrical with \(1 \text{ mm} \) diameter and a conical extremity, whereas plane-type electrodes have a flat surface, as presented in Fig. 4.2. The plane-type electrode surface is polished or milled by diamond fly-cutting. Table 1 summarizes the general setup used for the experiments.

Fig. 4.2: Electrode geometry configuration: (a) Point-to-plane; (b) Point-to-point.

Table 1: Electric discharge conditions

<table>
<thead>
<tr>
<th>Variables of the process</th>
<th>Working conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open voltage ( (U_{\text{open}}) )</td>
<td>250 ( V )</td>
</tr>
<tr>
<td>Electric current ( (I) )</td>
<td>10, 20 and 40 ( A )</td>
</tr>
<tr>
<td>Electric current pulse shape</td>
<td>Square and slope-shaped pulse</td>
</tr>
<tr>
<td>Pulse duration ( (t) )</td>
<td>316 ( \mu \text{s} )</td>
</tr>
<tr>
<td>Electrode geometry</td>
<td>Point-to-plane configuration</td>
</tr>
<tr>
<td>Electrode material</td>
<td>Copper and aluminum</td>
</tr>
<tr>
<td>Electrode polarity</td>
<td>Positive and negative</td>
</tr>
<tr>
<td>Dielectric media</td>
<td>Air and Oelheld IME 110 oil</td>
</tr>
</tbody>
</table>
4.1.1. Crater measurements

Morphology and dimension of craters left by single discharges on the electrode surface can provide important information about the plasma-material interactions that occur during the DEDM process. Therefore, craters formed by single discharges are measured and analysed in the present work.

A Leica DCM 3D microscope, shown in Fig. 4.3a, is used for 3D measurements of the craters. This equipment combines confocal and interferometry technologies, which allow confocal and bright field image measurements simultaneously. Surface measurements can be performed with resolutions < 1 nm [46]. In addition, the Leica Map 7.2 software is applied for the analysis of electrode surface measurements. An example of craters image generation is presented in Fig. 4.3b.

![Fig. 4.3: (a) Leica DCM 3D microscope; (b) Image of craters analysed by Leica Map 7.2.](image)

4.2. Electrical signal measurements

Electrical signal analysis is widely applied in EDM, since this provides important information for machining process monitoring and control. Electric current and voltage signals are acquired in the present work in order to analyse their time behaviour and quantify the electric discharge energy levels. These measurements can give indications on time-dependent EDM discharge properties, such as transient to steady-state transitions, supporting interpretation of optical plasma diagnostics.

Electric discharge current and voltage are acquired with a time resolution of 2 ns by a LeCroy Wave Runner 44MXi-A oscilloscope, which is connected to voltage and current probes. The voltage probe is a LeCroy PP008 with 500 MHz bandwidth, whereas the DC current probe is a Tektronix TCP0150 AC/DC. The used experimental setup is schematically shown in Fig. 4.4.
Fig. 4.4: Experimental setup for electrical signal acquisition

Single discharges performed in the present work start from an applied open voltage, which drops abruptly when the breakdown occurs and oscillates around a certain value that depends on the dielectric medium, electrode gap, electrode material and electric current. Typical electrical signal measurements are presented in Fig. 4.5a and Fig. 4.5b.

Fig. 4.5: (a) Electric discharge current; (b) Electric discharge voltage.

Since DEDM discharges are normally formed in very small gaps (< 5 µm) due to a vacuum breakdown mechanism, mechanical contact between electrodes eventually occurs before or even after the discharge ignition. This mechanical contact is named “short circuit”. Short circuits can be properly detected by electrical signal measurements, since the current flows in the circuit with small resistance, while the voltage is very low (< 6 V) when compared with the voltage of an EDM discharge. Experiments performed with the occurrence of short circuits are discarded from the present analysis.

4.2.1. High-speed imaging

EDM plasmas develop in the gap on the microsecond scale. Therefore, a fast camera is necessary for acquisition of images of the discharge. The time behaviour of some EDM plasma
properties, such as expansion and shape, are analysed here by high-speed imaging. Typical high-speed imaging is presented in Fig. 4.6 for discharges in air and oil dielectric. Furthermore, effects of the plasma-material interactions, such as the removal of debris from the crater region, can be estimated by this method. In particular, the time behaviour of the plasma expansion is a crucial information for further OES interpretation, since the plasma dimension is an important input for emission spectra simulations, as described in section 4.5.

![Plasma expansion analysis by high-speed imaging](image1)

**Fig. 4.6:** Plasma expansion analysis by high-speed imaging: (a) Electric discharge in air; (b) Electric discharge in oil; \( U_{\text{open}} = 250 \, V; I = 20 \, A; t = 316 \, \mu s; \) Copper point cathode and aluminium plane-type anode.

In order to acquire images of plasmas in oil, the discharges are performed in a chamber with a glass window. Moreover, high-speed imaging of discharges in liquid dielectric allows also measuring the dimensions of the gas bubble formed around the plasma, as highlighted in Fig. 4.6b. The dynamics of the gas bubble formed in EDM can have substantial effect on the material removal mechanism, as explained by Zhang et al. [141]. The high-speed imaging experimental setup used in the present work is presented in Fig. 4.7.

![High-speed imaging setup](image2)

**Fig. 4.7:** High-speed imaging setup

High-speed imaging is performed by a Vision Research Phantom V12.1 (maximum of 1 million frames/s and minimum 300 ns exposure time) equipped with a telecentric lens. The high-speed camera is triggered by the oscilloscope from an increase of the measured electric current, which occurs when the discharge starts. It is important to highlight that the frame
rate of the high-speed camera is selected considering the light intensity acquisition and the number of active pixels of the CMOS sensor. The higher the frame rate, the lower the light intensity and the resolution of the acquired image.

4.3. Optical emission spectroscopy

Optical emission spectroscopy is a widely applied non-intrusive plasma diagnostic and is used here to investigate EDM plasma properties. This diagnostic basically consists in an analysis of the visible light emitted by the plasma, from which several of its parameters can be estimated. The optical emission spectrum is obtained in the spectrograph and recorded by a photodetector. The experimental setup is designed for time and spatially-resolved OES, as described in the sections 4.3.1 and 4.3.2.

4.3.1. Time-resolved OES

OES is performed in the present work by acquiring visible EDM plasma light with an Ø 1 mm quartz optical fibre bundle. The optical fibres are of the type SFS400/440T and have their input positioned near the erosion gap. The plasma light that reaches the optical fibres input, within the area given by their numerical aperture, is guided into an Acton Research Spectrograph 0.275 m from Princeton Instruments. The spectrograph forms the optical emission spectra dispersing the light by 150 l/mm gratings, which give a wavelength resolution of 0.263 nm. In order to reduce light intensity losses, which can be critical due to the short and weak EDM plasma light emission, the spectrograph has a W-configuration design with 2 silver-coated mirrors. The high-speed camera, the same as for high-speed imaging, is connected to the spectrograph output in order to record the optical emission spectra. The sensitivity of the camera CMOS sensor depends on the wavelength, as presented in Fig. 4.8.

![Spectral intensity response of the high-speed camera CMOS sensor](image)

Fig. 4.8: Spectral intensity response of the high-speed camera CMOS sensor [47]
Since the sensitivity of the CMOS sensor depends on the wavelength of the recorded light, the spectral behaviour of the detector needs to be calibrated. This allows as well obtaining the absolute intensity of the studied spectral lines. The intensity calibration is performed by multiplying the measured optical emission spectra by the calibration curve, which is shown in Fig. 4.9. This calibration curve is obtained by dividing the known light emission reference curve of a deuterium and tungsten halogen calibration light source by its acquired light spectrum.

![Calibration factor used for light intensity correction](image)

The emission spectra wavelength needs to be calibrated every time the high-speed camera is mounted in the spectrograph, since it leads to changes in the setup. This calibration is made using as reference some known spectral lines of the acquired plasma light, such as Al I at 396.15 nm, Cu I at 521.82 nm and Hα at 656.27 nm. The spectrograph is set with the central wavelength 550 nm, whereas the minimum and maximum wavelengths of the formed optical emission spectra are around 380 nm and 740 nm respectively. The input of the spectrograph, where the optical fibre is connected, has a vertical slit. This slit is set in the present work with the aperture of 20 µm in order to fit the light acquisition with the dimension of the CMOS sensor pixels of the high-speed camera. Furthermore, the high-speed camera is triggered by the current signal acquired by the used oscilloscope, as described in section 4.2.1. The OES setup is schematically presented in Fig. 4.10.

Optical emission from different regions of the plasma is acquired and integrated by summing the light collected by columns of pixels of the CMOS sensor. The light integration from all fibres of the bundle allow obtaining intensities high enough for time-resolved OES, since light collected by each fibre separately is too weak in this experimental arrangement for a proper signal-to-noise ratio. Light acquired by each column of pixels is associated with a corresponding wavelength within the spectrum resolution. The integration of the Hα line from several fibres, for example, is schematically shown in Fig. 4.11. In addition, time-resolved OES is performed by recording the plasma light emission during fixed time intervals of around 30 µs of a single discharge, as presented in Fig. 4.12.
EXPERIMENTAL SETUP AND PLASMA DIAGNOSTICS

Fig. 4.10: Experimental setup of time-resolved OES

![Experimental setup diagram]

Fig. 4.11: H$_\alpha$ spectral line generation from the integration of light collected by columns of pixels; Electric discharge plasma at 160 $\mu$s after the ignition; $U_{open} = 250 \, V$; $I = 20 \, A$; Copper point cathode and aluminium plane-type anode.

The generated optical emission spectra need additional processing for proper interpretation. Light acquired from the environment is removed by subtracting the background light from the optical emission spectra. The background light image is obtained from the emission spectrum acquisition by the CMOS sensor before the discharge ignition. Furthermore, in order to calculate the electron density of discharges in oil as dielectric, the base line resulting from the strong continuum radiation is removed.

Presence of intense broadband continuum radiation in optical emission spectra of EDM plasmas was also reported by Descoeudres [23], who infers that the continuum radiation is most probably originated from light given by recombination processes (free-bound...
transitions), free electrons that lose energy by passing near an atom or an ion (free-free transitions) and molecular broadband emissions. The electron density is calculated from the H$_\alpha$ spectral line broadening through a method that is explained in section 4.4.2.

![Graph showing Cu I transitions](image)

**Fig. 4.12:** Time-resolved optical emission spectra; $U_{\text{open}} = 250 \, V$; $I = 20 \, A$; $t = 316 \, \mu s$; Copper electrodes material; Point cathode and plane-type anode geometry.

### 4.3.2. Spatially-resolved OES and Abel inversion

An optical system was designed specifically to perform spatially-resolved OES in the present work. This optical system consists in a row of $\varnothing$ 100 $\mu m$ optical fibres equally spaced with a distance of 160 $\mu m$ between their centres. The fibre row is connected with a tube that has assembled a N-BK7 bi-convex lens with 15 $mm$ focus length and an ACL1210U-A aspheric condenser lens with 10.5 $mm$ focus length. The lenses are positioned according to their focus length, as shown in Fig. 4.13.

The optical system is used to increase the spatial resolution of the plasma light acquisition, which is an important factor to be considered for further Abel inversion analysis. The bi-convex lens distributes the plasma light over an area that corresponds to 3 times the original plasma dimension. The distributed light passes through the aspheric condenser lens, which collimates the light before it reaches the optical fibres input. The total number of illuminated fibres is around 15. Based on the light distribution by the optical system, one can estimate the size of the plasma regions from which each fibre collects light. Thus, for a plasma dimension of 400 $\mu m$, each fibre of the row collects light from a lateral plasma region of around 25 $\mu m$. Finally, the optical fibre row guides the plasma light into the spectrograph, as schematically shown in Fig. 4.14.
Experimental Setup and Plasma Diagnostics

Since the plasma light emission is distributed over a large number of fibres in the experimental setup for spatially-resolved OES, the amount of light per fibre is much smaller than the one achieved with the experimental setup for time-resolved OES, described in section 4.3.1. Due to this reason, no time-resolved measurements are possible with the experimental arrangement described here, so the photodetector acquisition time needs to be longer than the discharge duration.

The emission collected by each fibre of the row contains the integration of the local emission coefficient $\varepsilon(r)$ along the line of sight of a specific region of the plasma cross-section, assuming that the absorption within the plasma is negligible. Light collected over the whole plasma cross-section by the fibres row leads to a radiance profile in the form of a discrete set of data points, as schematically shown in Fig. 4.15. Several properties of specific regions of the plasma can be obtained by a further processing of the acquired radiance profile by Abel inversion, as described by Kunze [70].
Fig. 4.15: Radiance profile of an EDM plasma [70]

The Abel inversion, also known as inverse Abel transformation, is a mathematical method by which a circularly symmetric two-dimensional function can be reconstructed from its projection onto an axis, as explained by Smith et al. [116]. As described by Kunze [70], this calculation method can be applied for derivation of local emission coefficients of a cylindrical and symmetric plasma column by measuring the radiance of the plasma over its cross-section. The local radiance \( L(y) \) at the plasma shell can be calculated by the continuous function

\[
L(y) = 2 \int_{0}^{x_{\text{max}}} \varepsilon(r) dx
\]  
(4.1)

Since cylindrical symmetry of the plasma column is assumed,

\[
x^2 = r^2 - y^2
\]  
(4.2)

the one-dimensional profile of the radiance can be calculated by the Abel type equation

\[
L(y) = 2 \int_{0}^{\sqrt{R^2-y^2}} \varepsilon(r) dx = 2 \int_{y}^{R} \varepsilon(r) \frac{r dr}{\sqrt{r^2 - y^2}}
\]  
(4.3)

The local emission coefficient \( \varepsilon(r) \) is recovered by the Abel inversion, which can be represented by

\[
\varepsilon(r) = -\frac{1}{\pi} \int_{r}^{R} \frac{dL(y)}{dy} \frac{dy}{\sqrt{y^2 - r^2}}
\]  
(4.4)

Kunze [70] explains that Abel inversion calculations are very sensitive to the noise and errors in the measured radiance \( L(y) \). In addition, the discontinuity of (4.4) at \( y = r \), the dependence of (4.4) on the first derivative of the light intensity \( I_L(y) \) due to its increase by random dispersion of the measured data and the limited number of discrete \( I_L(y) \) values are the main problems that the Abel inversion algorithm needs to solve, as described by Sáinz et al. [111]. The relatively small number of \( I_L(y) \) data points acquired in the present work, which
corresponds to the light collected by each optical fibre, is particularly critical for the Abel inversion. In total, around 15 fibres collect plasma light. Therefore, assuming plasma symmetry, between 7 and 8 data points can be considered for the Abel inversion.

The accuracy of the Abel inversion calculations can be improved by an appropriated smoothing of the analysed discrete data points using fitting or numerical methods. The investigation reported by Sáinz et al. [111] indicates that, considering a number of $I_L(y)$ data points $\leq 15$, the widely used Nestor-Olsen method [95] is a suitable fitting approach for the Abel inversion application.

The Nestor-Olsen method is known for its simple computational implementation. This method assumes that the first derivative $I_L'(y^2)$ is constant over each small interval $\Delta y$ and is summarized by Sáinz et al. [111] as

$$\varepsilon_k(r) = -\frac{2}{\Delta y n} \sum_{n=k}^{N-1} I_{k,n}(y) B_{k,n} \quad (4.5)$$

where $k$ and $n$ are the integer position indexes for radial and lateral intensities, whereas $\Delta y$ is the width between two adjacent experimental data. The coefficient $B_{k,n}$ is calculated by

$$B_{k,n} = -A_{k,n} \text{ for } n = k \quad (4.6)$$

and

$$B_{k,n} = A_{k,n-1} - A_{k,n} \text{ for } n \geq k + 1 \quad (4.7)$$

where

$$A_{k,n} = \frac{[n^2 - (k - 1)]^{1/2} - [(n - 1)^2 - (k - 1)^2]^{1/2}}{2n - 1} \quad (4.8)$$

### 4.4. Plasma properties estimations from OES

A few properties of EDM plasmas have been reported in the literature, estimated directly from OES. Electron temperature is commonly calculated by the two-line Boltzmann method, whereas electron density is estimated from the $H_\alpha$ spectral line shift and broadening. These methods are also used in the present work and summarized in the following sections.

#### 4.4.1. Two-line Boltzmann method

Light is emitted from an atom or an ion with wave frequency $\nu_{pq}$ when a bound electron suffers a transition from an upper $p$ to a lower level $q$ of energy $E_L$ according to

$$\nu_{pq} = \frac{E_L(p) - E_L(q)}{h} \quad (4.9)$$
where $h$ is the Planck constant. The intensity of spectral lines is associated with the electron temperature of the plasma.

Assuming LTE, the two-line Boltzmann method is used in the present investigation to estimate the electron temperature of DEDM plasmas. This method is based on measurements of the intensity ratio of two selected spectral lines $I_{R_1}/I_{R_2}$ emitted by atoms or ions of the same element. Griem [36] describes that the electron temperature $T_e$ of a plasma can be calculated by

$$T_e = \frac{E_{L_2} - E_{L_1}}{k_B} \cdot \left[ \ln \left( \frac{I_{R_2} \lambda_2 g_2 A_2}{I_{R_1} \lambda_1 g_1 A_1} \right) \right]^{-1}$$

(4.10)

where $k_B$ is the Boltzmann constant, whereas $\lambda_1$ and $\lambda_2$ are the wavelengths, $A_1$ and $A_2$ the probabilities of state transition, $g_1$ and $g_2$ the statistical weights of the excited level and $E_{L_1}$ and $E_{L_2}$ the energy levels of the two selected spectral lines. $E_L$, $\lambda$, $A$ and $g$ are known parameters of the selected spectral lines, available in the National Institute of Standards and Technology (NIST) online database [104], while the relative intensity $I_R$ is measured.

The accuracy of the electron temperature calculation is substantially affected by the selection of the spectral lines for the application of the two-line Boltzmann method. The electron temperature calculation error depends on $|E_{L_2} - E_{L_1}|$, which must have a value as large as possible. Selection of spectral lines well isolated from other emission lines is also recommended in order to avoid overlapping and minimize $\Delta(I_{R_1}/I_{R_2})$. The electron temperature calculation error can be estimated by

$$\frac{\Delta T_e}{T_e} = \frac{k_B T_e}{|E_{L_2} - E_{L_1}|} \cdot \frac{\Delta(I_{R_1}/I_{R_2})}{I_{R_1}/I_{R_2}}$$

(4.11)

It is important to state that, in case of strong absorption of light emission by the dielectric medium, the selection of spectral lines with $\lambda_1$ and $\lambda_2$ close to each other is recommended. Despite all the above-mentioned considerations, an error of at least ±10% needs to be assumed for electron temperature calculations, since relative intensity calibration errors are rarely below this value, as highlighted by Griem [36].

**4.4.2. Electron density calculations**

The electron density $N_e$ ($cm^{-3}$) of electric discharge plasmas is estimated in the present work from the full width of a half maximum (FWHM) $\Delta \lambda_W$ (nm) of the measured H$\alpha$ spectral line using the theories of Gigosos et al. [33] with the equation

$$N_e = 8.8308 \cdot 10^{16} \cdot (\Delta \lambda_W)^{1.6005}$$

(4.12)

The H$\alpha$ spectral line is selected for electron density calculations due to its well-known broadening mechanism. The broadening of H$\alpha$ is dominated by the Stark effect, which is very
sensitive to the electron density of cold and dense plasmas. Descoeudres [23] describes that the Stark effect occurs due to collisions between emitters and charged perturbers, which lead to the formation of an electric field that modifies the atomic quantum levels of the emitters. In contrast, the broadening of metallic lines is substantially less sensitive to the Stark effect, which makes measurements of the \( \text{H}_\alpha \) broadening more suitable for electron density estimations in the present work.

Since spectral lines of dense plasmas have a shape close to a Lorentzian, a Lorentz fit curve is applied to the \( \text{H}_\alpha \) line before the electron density calculations, as shown in Fig. 4.16. The coefficients of the Lorentz curve are obtained from a non-linear least square fit, which iteratively finds the best set of coefficients to match the Lorentz curve to the measured intensity curve.

![Lorentz curve fitted to a \( \text{H}_\alpha \) spectral line](image)

Fig. 4.16: Lorentz curve fitted to a \( \text{H}_\alpha \) spectral line

### 4.5. Collisional-radiative models

Optical emission spectra contain much more information about the plasmas than the methods widely applied in the EDM literature, such as the ones presented in sections 4.4.1 and 4.4.2, can provide. Collisional radiative models can be used to estimate the plasma properties from its optical spectra thanks to the advances in collecting basic data and information on atomic and molecular physics. These calculations, used here for micro discharge plasma investigations, are currently possible for almost all atoms and molecules under many different plasma conditions.

#### 4.5.1. Rate equations

Beyond electron temperature and density, other important plasma properties can be analysed from the light emitted by an electric discharge. However, estimation of several plasma parameters, such as atom and ion densities, fraction of ionic species, plasma composition and electron energy distribution, needs the application of a model of the radiation process within the plasma. With the support of this model, the population densities of the excited states of the atomic species can be calculated from measurements of lines emission.
As explained by Kunze [70], the density $n_z(p)$ of species of charge $z$ in the upper state $p$ is simply proportional to their transition probability to the lower level $q$ described as

$$-\frac{dn_z(p)}{dt} \bigg|_{p\rightarrow q} = A_z(p \rightarrow q)n_z(p) \tag{4.13}$$

where $A_z(p \rightarrow q)$ is an atomic constant for this particular transition, known as atomic transition probability or Einstein coefficient of spontaneous emission. Since a photon is emitted with each transition, the emission coefficient $\varepsilon$ of the line is given by

$$\varepsilon(p \rightarrow q) = \frac{h\nu_{pq}}{4\pi} A_z(p \rightarrow q)n_z(p) \tag{4.14}$$

Kunze [70] describes that the kinetics of local populations of atomic states $s$ of ions of charge $z$ involved in electric discharges are governed by coupled rate equations of the type

$$\frac{dn_z(s)}{dt} = -C_z(s \rightarrow) + C_z(\rightarrow s) + \Gamma_z(s) \tag{4.15}$$

where $C_z(s \rightarrow)$ and $C_z(\rightarrow s)$ represent the sums of all rates of possible radiative and collisional transitions out of energy level $s$ and into energy level $s$, whereas $\Gamma_z(s)$ is the external flux of level-$s$ population by diffusion and convection. Eq. (4.15) considers a large number of transitions, some of them with unknown parameters, which makes its solution practically impossible.

Collisional-radiative models have been developed based on the physical principles of (4.15) with a reduced set of coupled rate equations, which consider only the most relevant processes and pertinent time scales. Advanced interpretation of OES is supported in the present work by the CR commercial code PrismSPECT [82]. PrismSPECT uses cross-sections generated by the ATBASE suit of codes developed by Wang [132], while line broadening mechanisms are also taken into account for the calculations, such as Doppler, natural and Stark broadening. In addition, PrismSPECT also calculates collisional excitation and ionization rates of plasmas with a non-Maxwellian electron energy distribution, such as an electron beam. Synthetic emission spectra are generated using the formulation proposed by Chung et al. [19], which can be written as

$$\frac{dn_z(p)}{dt} = -n_z(p)\sum_{q \neq p}^{N_L} W_{pq} + \sum_{q \neq p}^{N_L} n_z(q)W_{qp} \tag{4.16}$$

for upward transitions and

$$W_{pq} = B_{pq}\bar{I}_{pq} + n_e C_{pq} + \beta_{pq} + n_e \gamma_{pq} + \sigma_{pq} + \Gamma_{pq} \tag{4.17}$$

for downward transitions.
Experimentation Setup and Plasma Diagnostics

\[ W_{qp} = A_{qp} + B_{qp} \bar{J}_{qp} + n_e D_{qp} + n_e \alpha_{qp} + n_e \kappa_{qp} + n_e^2 \delta_{qp} \]  

(4.18)

where \( p \) is a lower energy state, \( q \) is an upper energy state, \( N_L \) is the number of energy levels included in the calculations and \( \bar{J} \) is a frequency-averaged mean intensity, which is relevant to the transition. Furthermore, the rate coefficients, which depend on discharge plasma parameters such as temperature and density of electrons, correspond to the following atomic processes:

- \( A_{qp} \) spontaneous emission: process of photon emission due to the transition from an excited energy state \( q \) to a lower energy state \( p \) of an atom, ion or molecule;
- \( B_{pq} \) stimulated absorption: process in which an atom, ion or molecule achieves a higher energy state \( q \) due to the absorption of a photon;
- \( B_{qp} \) stimulated emission: process in which an atom, ion or molecule achieves a lower energy state \( p \) due to the emission of a photon;
- \( C_{pq} \) collisional excitation: process of transition to an upper energy level \( q \) with excitation of an atom, ion or molecule given by its collision with a high-energy electron;
- \( D_{qp} \) collisional deexcitation: process of transition to a lower energy level \( p \) with deexcitation of an atom, ion or molecule given by its collision with a high-energy electron;
- \( I_{pq} \) beam and non-thermal electron collisions: signatures left on the optical emission spectra due to non-Maxwellian electron energy components within the plasma, which lead to the transition of an atom or ion to an upper energy level \( q \);
- \( \alpha_{qp} \) radiative recombination: process of transition of an ion to a lower energy level \( p \) due to the recombination with an electron, giving off the residual energy in the form of radiation;
- \( \beta_{pq} \) photoionization plus stimulated recombination: processes of transition of an atom or a molecule to a higher energy level \( p \) due to collisions with photons, which cause ionization and recombination respectively;
- \( \gamma_{pq} \) collisional ionization: process of transition of an atom or a molecule to a higher energy level \( p \) due to the ionization given by its collision with a high-energy electron;
- \( \delta_{qp} \) collisional recombination: process of transition of an atom or a molecule to a higher energy level \( p \) due to recombination given by its collision with a high-energy electron;
- \( \kappa_{qp} \) electron capture: process in which the nucleus of an electrically neutral atom absorbs a \( K \) or \( L \) shell electron, leading to its transition to a higher energy level \( p \) and converting a proton into a neutron;
- \( \sigma_{pq} \) autoionization: process of transition of an excited atom or molecule to a higher energy level \( p \) due to the spontaneous emission of one of its outer-shell electrons.
4.5.2. Radiation transport equations

Radiation emitted from an electric discharge can be re-absorbed within its plasma. This phenomenon depends on the plasma optical depth, as described by Kunze [70]. A plasma is named “optically thin” when re-absorption of its emission lines can be neglected. In contrast, when re-absorption of at least one emission line within the plasma takes place, the plasma is termed “optically thick”. The change of the spectral radiance \( L_\lambda(x, \lambda) \) by a thin slab of a plasma due to absorption in the direction \( x \) is given by

\[
dL_\lambda(x, \lambda) = -\kappa(x, \lambda)L_\lambda(x, \lambda)dx
\]  

(4.19)

where \( \kappa(x, \lambda) \) is the wavelength-dependent absorption coefficient. Additionally considering the emission by the plasma slab \( \varepsilon_\lambda(x, \lambda) \), the total change of the radiance becomes

\[
dL_\lambda(x, \lambda) = \varepsilon_\lambda(x, \lambda)dx - \kappa(x, \lambda)L_\lambda(x, \lambda)dx
\]  

(4.20)

The equation of radiative transfer is obtained from the division of (4.20) by \( dx \), as schematically presented in Fig. 4.17, which leads to the equation

\[
\frac{dL_\lambda(x, \lambda)}{dx} = \varepsilon_\lambda(x, \lambda) - \kappa(x, \lambda)L_\lambda(x, \lambda)
\]  

(4.21)

Kunze [70] introduces the optical depth of the thin slab shown in Fig. 4.17 by

\[
d\tau = -\kappa(x, \lambda)dx
\]  

(4.22)

Thus, the optical depth along a specific distance within the plasma can be calculated by

\[
\tau(x, \lambda) = -\int_0^x \kappa(x', \lambda)dx'
\]  

(4.23)

with \( \tau = 0 \) at the plasma surface \( (x = 0) \). The total optical depth governs the significance of the radiative transport at a specific wavelength. The optical depth is assumed in PrismSPECT to correspond to the number of mean-free paths of a photon at frequency \( \nu \) along the considered line of sight. Self-absorption needs to be considered when the optical depth at frequency \( \nu \) is larger than unity. In other words, lines emitted from a plasma with \( \tau > 1 \) are optically thick, whereas lines with \( \tau \ll 1 \) are optically thin, as described by Chung et al. [19].

Considering the integration along the line of sight of the plasma, (4.21) can be written as

\[
\frac{dL_\lambda(x, \lambda)}{d\tau} = \frac{\varepsilon_\lambda(x, \lambda)}{\kappa(x, \lambda)} = L_\lambda(x, \lambda) - S_\lambda(x, \lambda)
\]  

(4.24)

where \( \varepsilon_\lambda(x, \lambda)/\kappa(x, \lambda) = S_\lambda(x, \lambda) \) is the source function, for which induced emission and scattering of radiation needs to be considered. Finally, assuming no radiation incident on the plasma at \( x = -l \), as schematically shown in Fig. 4.17, the radiance at the plasma surface can be obtained by
\[ L_\lambda(0, \lambda) = \int_0^\infty S_\lambda(\tau, \lambda) e^{-\tau} d\tau \tag{4.25} \]

Fig. 4.17: Geometry of radiation transport [70]

4.5.3. Plasma properties estimation method

The method of plasma analysis used in the present work relies on direct comparisons between experimental and simulated emission spectra, from which important micro discharge plasma properties are deduced. The main CR code inputs and method used for plasma properties estimation are presented in the following:

- Plasma dimension: indications on the studied plasma dimensions are obtained here by its measurements with high-speed imaging, characterization of craters left on the electrode surface and spectroscopic analyses reported in the literature.

- Plasma composition: knowledge about the material of the electrodes applied in the discharges gives a first guess about the lines present in the emission spectra. Since copper and aluminium are used as electrodes in the present work, these materials are set in PrismSPECT. In addition to the lines emitted by elements from the electrode material, some other lines can be identified, such as H\textalpha, H\textbeta and N\textsubscript{2}. The emitting species considered for the simulations are listed in Table 2. Fig. 4.18 shows the emission spectrum of a DEDM discharge with identification of the emission lines. The fractions of plasma chemical elements are estimated from a first fit between the spectral lines of the dominant emitting species, which in the present investigation is Al. After the fit between observed and simulated Al spectral lines, the fraction of each one of the other elements (Cu and H) is progressively increased in the simulation set. The obtained synthetic spectrum is compared with the experimental one after each change in the plasma composition until the observed and simulated emission spectra completely match. PrismSPECT works with an atomic database in which molecular transitions are not included. Therefore, the possible molecular band of N\textsubscript{2}, with its peak at around 589 nm, is not considered for the simulations. A fit between experimental and simulated spectra is presented in Fig. 4.19.

- Density of atoms and ions: the first approximation for the density of atoms and ions is given by the electron density value calculated from the FWHM of the H\textalpha line, as
explained in section 4.4.2. Afterwards, the density of atoms and ions is estimated from comparisons and fitting between the height and broadening of the experimental and synthetic $H_\alpha$ emission lines. Since the optical emission spectrum results from an integration of the entire acquired plasma light, the obtained density of atoms and ions is an average value of each analysed time step of the discharge.

![Optical emission spectrum](image)

**Fig. 4.18:** Optical emission spectrum of an electric discharge at 160 $\mu s$ after the ignition; Copper point cathode and aluminium plane-type anode; $I = 20 A; U_{open} = 250 V$.

- **Transient / Steady state plasma:** temporal characteristics of the plasma can be analysed with the support of PrismSPECT by applying its time-dependent atomic rate equations; however, the transient state function of PrismSPECT does not allow the fractions of plasma components (Al, Cu and H) to change during the time. Therefore, the emission spectra simulations are performed in the present work using the steady state atomic rate equation for each time step of the studied single discharge, which can provide some indications on its temporal properties.

- **Spectral resolution:** is set in PrismSPECT after the generation of the synthetic spectrum. In the present work, the spectral resolution of 0.263 nm is set, since this is the resolution of the used spectrograph.

- **Electron energy distribution:** PrismSPECT calculates emission spectra of plasmas with a non-Maxwellian electron energy distribution. The fraction of a non-thermal electron component and its energy can be set in the software. The hypothesis of plasmas with a non-Maxwellian electron energy distribution is analysed in detail in section 5.2.3.

- **Electron temperature:** is estimated from comparisons between observed and simulated spectral lines intensity. The measured optical emission spectra are
multiplied by a factor in order to normalize one of the selected optical emission lines to its respective simulated one. In the present work, the Al I line at 396.15 nm is selected as a reference for the normalization, since it is well isolated and has high intensity, as shown in Fig. 4.20. Once the optical emission spectrum is normalized to the synthetic one, different plasma temperatures are set in PrismSPECT for comparison with the experiment. As a first approximation, electron temperatures obtained by the two-line Boltzmann method, described in section 4.4.1, are used. Furthermore, identification and characterization of an electron temperature profile within the plasma can be performed with support of emission spectra simulations. This subject is treated more in detail during the DEDM plasma analysis, presented in sections 5.2.2 and 5.2.3.

![Observed spectrum vs. Synthetic spectrum](image.png)

Fig. 4.19: Al and H lines used for plasma property estimation

Other inputs of PrismSPECT, such as plasma geometry and adopted atomic database, are described during the analysis of the optical emission spectra and estimation of DEDM plasma properties. Some properties of the plasma are calculated by PrismSPECT from the given input parameters, such as electron density, ionization and optical depth.

The proportion of ionic species of a plasma in LTE is calculated by PrismSPECT from statistical mechanics. The ratio of the excited states to the ground states within each ion stage is obtained by the Boltzmann equation, whereas the equations for the ratio of the ground state of successive ionization stages are given by the Saha-Boltzmann equation. Furthermore, from given atom and ion densities and assuming a temperature-dependent Thomas-Fermi approximation, the plasma mean charge and the electron density of the plasma are estimated. The complexity increases substantially for the calculation of fractions of ionic species of a plasma which is not in equilibrium and/or has considerable optical depth effects. In these cases, some rate coefficients depend on the ion population densities, and therefore, the equations are solved by PrismSPECT numerically, as described by Chung et al. [19].
Fig. 4.20: Al I lines used as reference for normalization and electron temperature estimation

Table 2: Spectral lines considered for OES analysis

<table>
<thead>
<tr>
<th>Emitting species</th>
<th>λ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al I</td>
<td>394.40</td>
</tr>
<tr>
<td>Al I</td>
<td>396.15</td>
</tr>
<tr>
<td>Al II</td>
<td>466.30</td>
</tr>
<tr>
<td>Al II</td>
<td>559.33</td>
</tr>
<tr>
<td>Al II</td>
<td>623.17</td>
</tr>
<tr>
<td>Al II</td>
<td>624.34</td>
</tr>
<tr>
<td>Al II</td>
<td>704.21</td>
</tr>
<tr>
<td>Al II</td>
<td>705.67</td>
</tr>
<tr>
<td>Al III</td>
<td>447.98</td>
</tr>
<tr>
<td>Al III</td>
<td>451.89</td>
</tr>
<tr>
<td>Al III</td>
<td>452.92</td>
</tr>
<tr>
<td>Al III</td>
<td>569.66</td>
</tr>
<tr>
<td>Al III</td>
<td>572.27</td>
</tr>
<tr>
<td>Cu I</td>
<td>515.32</td>
</tr>
<tr>
<td>Cu I</td>
<td>521.82</td>
</tr>
<tr>
<td>Hα</td>
<td>656.27</td>
</tr>
<tr>
<td>Hβ</td>
<td>486.13</td>
</tr>
</tbody>
</table>
5. DEDM DISCHARGE DIAGNOSTICS

The present chapter introduces well-established diagnostics from the field of plasma physics as successful tools for DEDM discharges analysis. Several important plasma parameters, such as electron temperature and density, distribution of ionic species, fast electron populations and plasma composition are here estimated.

5.1. DEDM plasma composition

5.1.1. Optical emission spectra analysis

Specific spectral lines are emitted by atomic and ionic species of a plasma. Therefore, some indications on the proportions of the different components of a DEDM plasma, which are linked to the populations of excited states of its atoms and ions, can be qualitatively deduced by an analysis of the time-resolved optical emission spectra. Time-resolved optical emission spectra of discharges performed with a copper point anode and an aluminium plane-type cathode in air are presented in Fig. 5.1.

![Figure 5.1: Time-resolved optical emission spectra of a single discharge; Copper point anode and aluminium plane-type cathode; $I = 20 \, A; U_{open} = 250 \, V; t = 316 \, \mu s.$](image)

Atomic Al I, H$_\alpha$ and Cu I lines and ionic Al II and Al III lines can be clearly observed in the optical emission spectra shown in Fig. 5.1. Al I, Cu I and H$_\alpha$ lines are emitted by the
neutral excited populations of the plasma, whereas Al II and Al III lines are emitted by its excited Al\(^{+1}\) and Al\(^{+2}\) ion populations respectively. The optical emission spectra change significantly when a copper point-type cathode is applied for the discharges. In this case, Al and H spectral lines have high intensity during the whole discharge duration, whereas Cu lines are just weakly present, as shown in Fig. 5.2. This observation suggests that the Cu cathode is not an active electrode in the discharge, with just small contribution of its material to the plasma composition.

Fig. 5.2: Time-resolved optical emission spectra of a single electric discharge; Copper point cathode and aluminium plane-type anode; \(I = 20\; A; U_{\text{open}} = 250\; V; t = 316\; \mu s\).

Interpretation of the optical emission spectra shown in this section agrees with experimental results reported by Kunieda et al. [67], who infer that the tool electrode wear in DEDM is very small and independent of the electric discharge pulse duration. In addition, observations of the optical emission spectra performed here suggest that the characteristics of the plasma of DEDM discharges performed with a point-type cathode tool might be similar to the ones of hot anode vacuum arcs (HAVA).

As described in section 2.3.1, the cathode works as source of electrons in a HAVA, whereas the anode and the inter-electrode plasma provide a large proportion of the energy that sustains the discharge. The cathode can be considered as an inert and relatively passive electrode due to its low activity in a HAVA. Although some similarities between DEDM discharges performed with a copper point-type cathode and a HAVA can be deduced from optical emission spectra observations, deeper insight into the discharges by more advanced plasma diagnostics is necessary in order to confirm this thesis. Diagnostics of HAVA discharges in large gaps reported in the literature are used to support the interpretation of the optical
emission spectra investigated in the present work, which are emitted from electric discharges in micrometre gaps.

5.1.2. Determination of plasma composition

OES interpretation supported by emission spectra simulations can give quantitative estimations on the DEDM plasma composition, which can provide important information concerning the activity of the electrodes during the discharge. The plasma composition is estimated here from comparisons between observed and synthetic optical emission spectra, which are simulated by the commercial CR code PrismSPECT. The emission spectra simulations are performed assuming discharges with a Maxwellian electron energy distribution. Time-dependent plasma composition and ion density with homogeneous spatial distribution are considered for the fitting procedure, as described in section 4.5.3.

Emission spectra simulations indicate that discharges performed with point copper anode and plane-type aluminium cathode are metallic plasmas with some contributions of hydrogen. As presented in Fig. 5.3a, the plasma contains a large fraction of both electrodes’ material. These observations suggest that both electrodes actively take part in the discharge, which is a characteristic of traditional vacuum arcs, as described by Boxman et al. [14]. These observations are in agreement with the tool electrode wear analysis reported by Kunieda et al. [69]. According to their experimental results, high tool electrode wear and low workpiece material removal rates are observed when DEDM is performed with an anode tool electrode.

In contrast, emission spectra simulations suggest that the plasma of DEDM discharges performed with point-type copper cathode are mostly composed of metal vapour originated from the anode material, as shown in Fig. 5.3b. This is a typical characteristic of a HAVA in large gaps. As reported by Bacon [6], the anode provide the metal vapour in which the arc burns, whereas just little cathode activity occurs. Thus, the determination of the fractions of plasma components by the CR model reinforces the hypothesis that HAVA discharges are formed in DEDM performed with a point-type cathode, as proposed in section 5.1.1.

The fraction of cathode material in the plasma reaches its maximum value immediately after the ignition, dropping during the discharge development. The relatively high copper composition of the plasma during the first 32 μs of the discharge also agrees with the start of HAVA out of a diffuse vacuum arc, which burns in the evaporated cathode material. Miller [88] explains that the anode dominated vacuum arc is finally formed due to the transition from the diffuse mode towards an anodic vacuum arc.

The reported similarities between DEDM discharges and HAVA are additionally supported by an analysis of the point-type copper electrode after DEDM processing. Fig. 5.4 presents the conditions of point-type copper electrodes after 30 discharges performed under different polarities. The pictures are from the top of the conical extremity of the electrodes. Craters are clearly formed on the anode tool surface, whereas the cathode tool does not have visible craters and is coated by aluminium, which is originated from the workpiece material.
Fig. 5.3: DEDM plasma composition determined by emission spectra simulations: (a) Copper point anode and aluminium plane-type cathode; (b) Copper point cathode and aluminium plane-type anode; $I = 20 \, A; U_{\text{open}} = 250 \, V; t = 316 \, \mu s$.

The low tool wear rates reported for DEDM in the literature can be explained by the fact that the energy of ions and neutrals coming from the anode is relatively low, so negligible cathode material sputtering takes place in a HAVA, as described by Miller [88]. Furthermore, the cathode is commonly a receiver of material from the anode, so the net cathode erosion can be negative. HAVA discharges are commonly used in coating process applications thanks to this characteristic, as explained by Boxman et al. [10]. Coating of a point-type cathode electrode by anode material was also reported in DEDM by ZhanBo et al. [138]. This is one more indication that DEDM discharges performed with point-type cathode are similar to HAVA discharges.

Fig. 5.4: Point-type copper electrode surface after 30 discharges: (a) Anode; (b) Cathode; $I = 20 \, A; U_{\text{open}} = 250 \, V; t = 316 \, \mu s$.

Emission spectra simulations indicate that a considerable fraction of hydrogen is present in the plasma of discharges performed with both electrode polarities. This probably occurs due to the high solubility of hydrogen in molten aluminium, which takes place by reactions of this metal with moisture of the melting environment, as reported by Lin et al.
Thus, the hydrogen composition of the plasma is probably originated from the workpiece material. A peak at the wavelength 589 nm is also detected and can probably be attributed to the emission lines from a N\textsubscript{2} band, as previously mentioned in section 4.5.3, originated from nitrogen of the surrounding atmosphere. Since vacuum discharges are dominated by metallic species, the presence of some N\textsubscript{2} probably does not affect the properties of the plasma and its interactions with the electrode material significantly.

5.2. Electron temperature and electron energy distribution

5.2.1. Two-line Boltzmann method

The temperature of the DEDM plasma is determined in the present section by the two-line Boltzmann method, described in section 4.4.1, assuming discharges in LTE and optically thin plasmas. The studied DEDM discharges are performed with point copper and plane-type aluminium electrodes.

The two-line method calculates a plasma electron temperature based on the intensity ratio of two strong and properly isolated spectral lines, which must be necessarily emitted from atoms or ions of the same element. In addition, the selected emission lines must have a high difference between their upper energy levels in order to reduce errors, as explained in section 4.4.1. Thus, the two Al I\textsubscript{II} emission lines at the 559.33 nm and 704.06 nm wavelengths were chosen for the electron temperature estimations.

The calculated electron temperatures are shown in Fig. 5.5 for single discharges performed with different electrode polarities. The calculations suggest that the temperatures are very similar for both polarities and slightly vary around 17,000 K (\( \approx 1.46 \text{ eV} \)), which indicates that the DEDM plasmas are cold (between 1 and 2 eV). The error bars in the graph of Fig. 5.5 are generated considering the temperature calculation error according to (4.11) and the minimum expected error of 10% proposed by Griem [36]. Several other researchers reported similar results for different EDM applications [23, 53, 61, 84, 93, 94, 117, 118]. Just a few of these authors investigated the plasma properties by spatially-resolved optical emission spectroscopy.

An electron temperature profile of DEDM plasmas was reported by Natsu et al. [93], who performed spatially-resolved optical emission spectroscopy processed by the Abel inversion. Kojima et al. [61] presented spatially-resolved optical emission spectroscopy of DEDM discharges, which gives some indications on a plasma temperature profile and qualitative spatial distribution of ionic species within the discharges. The investigations reported by those authors assume that the DEDM plasma are in LTE.

As explained by Descoeudres [23], the electrons of the weakly non-ideal EDM plasma in liquid dielectric are very rapidly thermalized due to the large amount of collisions between them. Therefore, a LTE condition of the plasma can be assumed. However, this assumption is not necessarily valid for DEDM plasmas, which can have lower density values than electric
discharges performed in liquid dielectric media, as reported by Kanmani Subbu et al. [53]. High electron density is particularly observed at the beginning of discharges in oil dielectric, as can be seen in section 6.3.

![Graph showing time-resolved electron temperature of DEDM plasmas performed with different electrode polarities; $I = 20 \ A; U_{\text{open}} = 250 \ V; t = 316 \ \mu s$.]

**5.2.2. Electron temperature profile**

Analysis of spatial properties of DEDM plasmas can reveal important information concerning their interactions with the electrode material. Therefore, a detailed analysis of the DEDM plasma temperature, assuming LTE, is presented in this section. Copper point cathode and aluminium plane-type anode are applied in the single discharge experiments reported here.

DEDM plasmas temperatures are around 1.46 $eV$, as the two-line Boltzmann method calculations reported in section 5.2.1 indicate. Due to this reason, emission spectra simulations are performed with the low temperature plasma database of PrismSPECT. Plane geometry of the plasmas is assumed for the simulations. In addition, the optical depth of the plasma needs to be considered for a proper spatial analysis of the discharges. Light emitted by the central region of the discharge contains important information, which might be self-absorbed by the plasma depending on its optical properties.

The emission spectra simulated by PrismSPECT show, by varying the plasma size at constant electron temperature and density, that the emission lines of the DEDM plasmas studied in the present work are optically thin. Fig. 5.6 shows the optical depth of all the analysed lines of a plasma with 500 $\mu m$ diameter, $T_e = 15,000 \ K$ and $N_e = 10^{17} \ cm^{-3}$, whereas the fraction of plasma components are $H_{fr} = 0.3, Al_{fr} = 0.6$ and $Cu_{fr} = 0.1$ for hydrogen, aluminium and copper respectively.
The maximum optical depth value observed in the graph of Fig. 5.6 is $\tau < 0.7$. As explained in section 4.5.2, the optical depth of a spectral line should be $\tau \geq 1$ for the occurrence of absorption within the plasma. Consequently, for DEDM plasmas with the dimensions observed in the present investigation, self-absorption of plasma light can be neglected for the analysis of its spatial properties.

Fig. 5.6: Simulation of the optical depth of a plasma with 500 $\mu$m diameter; $T_e = 15,000$ K; $N_e = 10^{17}$ cm$^{-3}$; $H_{fr} = 0.3$; $Al_{fr} = 0.6$; $Cu_{fr} = 0.1$.

Fig. 5.7 presents a comparison between experimental and simulated DEDM plasma emission spectra. The synthetic spectrum is calculated for a temperature $T_e = 15,000$ K. The comparison between the observed and simulated emission spectra shows that the experimental and calculated Al I and Al II spectral lines are found to properly match. However, no noticeable Al III spectral lines are observed for this plasma electron temperature, as highlighted in the inlet of Fig. 5.7.

A comparison between the same experimental spectrum shown in Fig. 5.7 and a synthetic one calculated for a higher electron temperature, $T_e = 20,800$ K, is presented in Fig. 5.8. This comparison indicates that matching between the most prominent Al II and Al III experimental and calculated emission lines is obtained at higher electron temperature, assuming the same discharge plasma dimension ($\phi 500$ $\mu$m) and electron density ($N_e = 10^{17}$ cm$^{-3}$). Nevertheless, Al I lines, as shown in the inlet of Fig. 5.8, have much lower intensity or are even not present in this synthetic spectrum. Thus, emission spectra simulations clearly indicate that a constant electron temperature profile does not allow explaining the experimental optical emission spectra from the analysed DEDM plasma. This result evidences that the discharge plasma must have an electron temperature profile peaking at its centre. The hypothesis of a temperature profile is schematically presented in Fig. 5.9.
Since the hypothesis of DEDM plasmas in LTE is considered in the current section, the presence of a plasma temperature profile is investigated. The measured spectral lines intensity is simultaneously linked to the electron temperature, population of emitting species...
and dimensions of the electric discharge plasma. Therefore, the investigation performed in the present section considers that a proper relation between these variables is necessary in order to obtain a synthetic spectrum that corresponds to the experimental observed one.

Fig. 5.9: Scheme of the DEDM plasma temperature profile

A discretization of the electron temperature profile is performed in order to simulate the optical emission spectra. Spatially-resolved OES together with the Abel inversion can provide DEDM plasma properties distribution over several data points in space, as reported in section 4.3.2. Since the OES reported in the present section is not spatially-resolved, some further assumptions need to be made. Specific characteristics of DEDM discharge and its interactions with the electrode material can provide some indications on the electron temperature profile. Therefore, in the present section, the plasma is assumed to be divided in distinct regions, from which a local average temperature can be estimated. Furthermore, the assumption of a minimum error of $\pm 10\%$ is considered for all the emission spectra simulations reported in this work due to spectrum intensity calibration uncertainties, as proposed by Griem [36].

The intensity of the plasma light collected by the optical fibres is proportional to the radiance $L$, which is calculated by (4.1). The radiance is integrated over the entire line of sight of the plasma, as previously presented in section 4.5.2. Considering plane geometry of the plasma and negligible self-absorption, for a piecewise constant $\varepsilon(s)$, the radiance can be approximated by

$$L \approx \sum_{i}^{N_z} \varepsilon(s_i) \Delta s_i \quad (5.1)$$

where $\varepsilon(s_i)$ is the constant emission coefficient in the interval $\Delta s_i$ and $N_z$ is the number of zones within the plasma with constant emission coefficient. In the present work, each optical
emission spectrum given by $\varepsilon(s)\Delta s_i$ is individually calculated by PrismSPECT. Based on the above-mentioned assumptions, the plasma is divided in several zones with different thickness ($\Delta s_i$) for the calculation of the total emission spectra. The total calculated emission spectra are obtained by summing the $\varepsilon(s)\Delta s_i$ contributions from those different discharge plasma regions.

The first plasma region assumed here is based on the total plasma plume dimension, which is measured by high-speed imaging. The plasma plume dimension reaches around 400 $\mu$m for the applied experimental conditions, as shown in Fig. 5.10. Since emission spectra simulations indicate that the DEDM plasma has a temperature profile, at least a second plasma region with a different temperature needs to be assumed. This second plasma region must have an average temperature value higher than the first mentioned region, leading to Al III lines emission. Since the crater generated by discharge plasma-electrode material interactions are smaller than the corresponding measured plasma dimension, its morphology can give some indications on regions of the plasma under high temperature. Therefore, a second plasma region is assumed in the present work according to the dimensions of craters left by single discharges. The craters are measured by confocal microscopy with the equipment described in section 4.1.1 and have an average diameter $\varnothing 185$ $\mu$m.

![Fig. 5.10: DEDM plasma expansion; Copper point cathode and aluminium plane-type anode; $I = 20$ A; $U_{open} = 250$ V; $t = 316$ $\mu$s.](image)

Emission spectra simulations indicate that the two assumed plasma regions, obtained from measurements of plasma dimensions and crater diameters, do not provide enough information for a proper DEDM plasma analysis. Comparisons between observed and simulated emission spectra lead to the following observations:

- The experimental and simulated Al III lines are correctly fitted, whereas the simulated Al II lines get much stronger intensities than the experimental ones;
- The experimental and simulated Al II lines are properly fitted, while the intensities of the simulated Al III lines become much higher than the experimental ones.

Therefore, a third region of the plasma needs to be introduced in order to better fit the synthetic emission spectra to the observed experimental one.
The third region of the plasma is defined according to spectroscopic measurements of HAVA discharges in large gaps reported by Bacon [6]. According to his results, this region is estimated to be between 3 and 5 times smaller than the total plasma channel dimension. Thus, in the present case, a size of 80 \( \mu m \) for the third plasma region is assumed, situated in the centre of the discharge. Fig. 5.11 presents the plasma regions assumed for the emission spectra simulations, which are referred as regions 1, 2 and 3.

Fig. 5.11: Crater left by a single DEDM electric discharge and respective assumed regions of a plasma electron temperature profile; Copper point cathode and aluminium plane-type anode; \( I = 20 A; U_{open} = 250 V; t = 316 \mu s \).

The electron temperature estimations concerning each time step of the analysed discharge plasma are performed in the present section according to the following topics:

- A first synthetic emission spectrum of a plasma is simulated with the electron temperature and density calculations obtained from the observed optical emission spectrum, according to sections 4.4.1 and 4.4.2 respectively. In addition, the plasma dimension is set in the simulation based on high-speed imaging measurements;
- The simulated spectrum is normalized to the experimental one using the Al I spectral line at the wavelength 396.15 nm as reference, as described in section 4.5.3;
- Atom and ion densities and hydrogen fraction of the plasma composition are set in PrismSPECT in order to fit the observed and simulated H\(_{\alpha}\) emission line;
- The first electron temperature is estimated from the best fit between synthetic and experimental Al II lines, while the plasma size corresponding to the region 2 is also set;
- The second electron temperature is estimated from the best fit between synthetic and experimental Al III lines. In this case, the plasma size corresponds to the region 3, where the plasma is considerably more ionized;
The two synthetic emission spectra generated according to the previous topics are summed and compared with the experimental one. Since both regions 2 and 3 contribute to Al II lines emission, the sum of the synthetic spectra results in a spectrum with Al II lines higher than the experimental observed ones;

The third electron temperature is estimated for region 1, which allows the final adjustments of the Al II lines from comparisons between the experimental and the summed synthetic spectrum. The region 1 has an electron temperature slightly lower than in region 2 and substantially lower than in region 3.

A comparison between the experimental and simulated emission spectra of the DEDM plasma in region 1 at 128 $\mu$s after the electric discharge ignition is shown in Fig. 5.12. Cu I spectral lines are emitted from the neutral excited vapour originated from the point-type cathode material, contributing only little to the observed optical emission spectrum. Strong lines are emitted from the neutral excited metal vapour from the anode material, while Al II spectral lines from ionic species are just weakly reproduced for the adopted electron temperature, as can be observed in Fig. 5.12.

![Experimental and simulated emission spectra at $T_e = 13,800$ K of the plasma region 1 at 128 $\mu$s after the ignition; Copper point cathode and aluminium plane-type anode; $I = 20$ A; $U_{\text{open}} = 250$ V.](image)

The emission spectra simulations indicate that the analysed DEDM plasma is mostly composed of different Al species, as beforehand reported in section 5.1.2. This characteristic is expected from anode dominated vacuum arcs performed with microsecond pulse duration, low electric current and aluminium anode, as reported by different researchers [6, 14, 89] in investigations concerning electric discharges in large gaps.
Further contributions of Al II spectral lines emission to the analysed spectrum are observed by adding the synthetic spectrum from region 2, which has an electron temperature slightly higher than the temperature of region 1. Finally, the best fitting emission spectrum, which results from the sum of the spectra contributions from regions 1, 2 and 3, matches with most of the experimentally observed emission lines, as presented in Fig. 5.13. Al III experimental spectral lines fit to the synthetic ones when light emitted from region 3 is considered, as shown in the inlet of Fig. 5.13.

![Emission spectrum comparison](image)

Fig. 5.13: Experimental and simulated emission spectra of the plasma region 1 ($T_e = 13,800 \, K$), region 2 ($T_e = 15,000 \, K$), and region 3 ($T_e = 22,000 \, K$) summed at $128 \, \mu s$ after the discharge ignition; Copper point cathode and aluminium plane-type anode; $I = 20 \, A$; $U_{open} = 250 \, V$.

Comparisons between experimental and simulated optical emission spectra for each time step of the electric discharge provide an estimation of the time and spatially-resolved electron temperature of the studied DEDM plasma. The electron temperature of the plasma calculated for regions 1 and 2 are very close, whereas region 3 presents substantially higher temperature values, if compared with the other two assumed regions. In addition, the time behaviour of the burning voltage might be attributed to the changes in the temperature profile, as shown in Fig. 5.14.

The root mean square (RMS) burning voltage increases from around 16 to 17 $V$ during approximately $100 \, \mu s$ after the electric discharge ignition, as can be observed in Fig. 5.14. Miller [89] infers that this behaviour can indicate a transition of the diffuse mode towards an anodic vacuum arc. This transition can be triggered by a magnetic constriction of the discharge in the gap, anode melting or a combination of both phenomena. Furthermore, the burning
voltage drops between the 100 µs and 220 µs after the discharge ignition. This probably occurs due to anode material melting and a hot spot formation. As described by Jakubowski et al. [50], the anode hot spot is a region of high temperature and large concentration of electrons near the anode surface.

Another indication that a hot spot is formed in the analysed DEDM discharges, according to the emission spectra simulations, is the electron temperature decrease in all the regions of the plasma until 220 µs after the discharge ignition. The electron temperature probably drops because the electric discharge energy is distributed over the rising metal vapour, as proposed by Kharin [56]. This leads to a reduction in the average kinetic energy of the particles in the plasma. Similar results were also presented by Grissom et al. [37] for microsecond vacuum arcs performed with low electric currents. Furthermore, the RMS burning voltage and the electron temperatures of regions 1 and 2 stay relatively constant after about 220 µs in the whole plasma, while the electron temperature of region 3 just slightly decreases. These characteristics suggest a transition from a transient to a steady-state electric discharge.

![Fig. 5.14: Electron temperature and RMS burning voltage during the time; Copper point cathode and aluminium plane-type anode; \( I = 20 \, A; U_{\text{open}} = 250 \, V \).](image)

**5.2.3. Electron energy distribution**

The current section reports on the hypothesis of the presence of a non-Maxwellian electron energy distribution within the studied DEDM plasmas. Copper point cathode and aluminium plane-type anode are used in the experiments, as also adopted in the previous section.

Several researchers [5, 7, 9, 13] have reported high electron energy and positive plasma potential near the anode of HAVA discharges in large gaps. According to Bacon et al.
[7], this phenomenon can occur due to a concentration of the discharge to a hot anode spot. Guile [38] explains that a voltage drop takes place in an extremely thin region near the anode surface due to its high concentration of electrons. A high number of positive ions is formed in the vicinity of the anode surface, while electrons are accelerated by the electric field, moving towards the anode. Thus, an anodic double layer is formed, composed of an acceleration zone and an ionization zone. Furthermore, the presence of an anodic double layer within the discharge leads to a potential profile with both positive and negative curvatures near the anode, as schematically presented in Fig. 5.15.

![Diagram of a discharge plasma](image)

**Fig. 5.15:** Space potential and anodic double layer of a discharge plasma, adapted from Bacon et al. [121]

As described in section 2.2, the magnetic field generated by the electron current flow can lead to a geometrical constriction of the energy flux to the anode, which is associated with the formation of a hot anode spot. In addition, the presence of an anodic double layer can contribute to the constriction of the discharge. As explained by Baalrud et al. [4], once a spot is formed in the vicinity of a proportionally large electrode surface, its effective electron collecting area shrinks in order to preserve the balance of electron and ion currents lost from the plasma. Thus, the constriction of the electric discharge can occur in order to reflect a fraction of the incident electron current.
Baalrud et al. [5] infer that a constriction of the electric discharge can lead to the formation of an electron beam. A fraction of electrons is highly accelerated by the anode potential fall, which can substantially affect the discharge dynamics and the necessary conditions for the equilibrium, as described in section 2.2. These authors also explain that, although electrons of the beam are responsible for high ionization, only a small fraction of its energy is lost to ionize neutral atoms. Since the anodic double layer potential structures present in a HAVA can lead to the formation of an electron beam, the occurrence of this phenomenon in the studied DEDM plasmas can be assumed as a feasible hypothesis for the simulation of the optical emission spectra.

The anode fall approximately corresponds to the ionization potential of the neutral gas in the gap, as explained by Baalrud et al. [5]. Since no gas is injected into the gap in the present experimental setup and the plasma of a HAVA is predominantly composed of metal vapour originated from the anode material, the anode potential fall value can be assumed to correspond to the aluminium vapour ionization energy $V_a = 5.986 \, eV$, as published by Liu et al. [74]. Furthermore, the DEDM plasma properties are estimated assuming the formation of an electron beam within the discharge. As schematically shown in Fig. 5.16, two distinct regions are assumed for the emission spectra simulations and their interpretation:

- Plasma plume region: delimited by the region formed between the electron beam region and the plasma shell;
- Electron beam region: central region of the plasma, which corresponds to the anode spot diameter.

Fig. 5.16: Electron beam and plasma plume regions

The diameter of the plasma shell varies from 250 $\mu m$ to 400 $\mu m$ during the time, as can be observed in Fig. 5.10. In addition, as previously mentioned in section 5.2.2, OES of
HAVA in large gaps reported by Bacon [6] shows that Al III species are concentrated within regions three to five times smaller than the total plasma dimension. This occurs due to a geometrical constriction of the discharge, which becomes concentrated to the anode spot. Therefore, the electron beam region is assumed to be a constricted and fixed region in the present work. In order to have a dimension three to five times smaller than the expanding plasma shell, as reported by Bacon [6], the electron beam region is circumscribed to a constant diameter $\phi = 80 \mu m$ at the centre of the plasma.

The sum of the simulated synthetic spectra, concerning the mentioned plasma plume and electron beam regions, is directly compared with the observed experimental emission spectrum in order to estimate the properties of the DEDM plasma. The total synthetic spectrum is calculated according to (5.1). Furthermore, spatial distribution of the DEDM plasma electron temperature is assumed to be piecewise constant, as proposed by Bacon et al. [7] for HAVA discharges with the presence of an electron beam. The optical emission spectrum of the discharge plasma is generated from the region restricted between the electron beam region, at the centre of the plasma, and the plasma shell, as schematically shown in Fig. 5.17.

The graph in Fig. 5.17 shows a comparison between observed and simulated emission spectra of the plasma plume region, which is modelled in PrismSPECT assuming a Maxwellian electron energy distribution. The comparison between experimental and synthetic emission spectra indicates that light emitted by the plasma plume contains Al I and Cu I lines, whereas Al II and H$\alpha$ experimental lines match just partially with the simulation. No Al III lines are emitted from this assumed region, as shown in one of the inlets of Fig. 5.17.

Fig. 5.17: Experimental and synthetic plasma plume spectra ($\phi_{plume} = 300 \mu m$, $T = 13,800 K$) at the 160 $\mu s$ after ignition of the electric discharge; Copper point cathode and aluminium plane-type anode; $I = 20 A$; $U_{open} = 250 V$.

The electron beam region is modelled in PrismSPECT assuming an electron beam energy that corresponds to the anode fall, whereas the fraction of electrons of the plasma
that belong to the beam is estimated by matching experimental and synthetic emission spectra, as shown in Fig. 5.18. Al III lines are only emitted from this region of the plasma, which agrees with the spectroscopic analysis reported by Bacon [6] and is compatible with the formation of a hot anode spot. The total synthetic spectrum is calculated from the sum of the plasma plume and electron beam regions according to (5.1), so the fit between experimental and synthetic spectra is obtained, as presented in Fig. 5.19.

Fig. 5.18: Experimental and synthetic plasma plume spectra ($V_a = 5.986 \, eV$, Fraction of high-energy electrons = 12%) at 160 µs after ignition of the electric discharge; Copper point cathode and aluminium plane-type anode; $I = 20 \, A$; $U_{open} = 250 \, V$.

Fig. 5.19: Experimental spectrum and summed synthetic spectra at 160 µs after ignition; Copper point cathode and aluminium plane-type anode; $I = 20 \, A$; $U_{open} = 250 \, V$.

Emission spectra simulated assuming electron beam dimensions smaller than 40 µm or larger than 130 µm do not fit to the observed experimental ones, which indicates that the...
hot anode spot must have a dimension within this range. Moreover, the synthetic spectrum of Fig. 5.18 indicates no emission of Cu I lines from the electron beam region, whereas Al I, Al II and Hα lines are only partially emitted. Furthermore, Fig. 5.20 shows that the electron temperature of the plasma slightly varies around 14,000 K (1.21 eV) during the time, while the high-energy electrons within the discharge clearly decrease. The reasons for this reduction of the high-energy electrons are not yet known and need further investigation.

Fig. 5.20: Electron temperature and fraction of high-energy electrons of the plasma; Copper point cathode and aluminium plane-type anode; \( I = 20 \, A; U_{\text{open}} = 250 \, V; t = 316 \, \mu s \).

5.3. Distribution of ionic species

Analysis of the ionic species composition can give important information about the discharge plasma. Therefore, in the present section, the spatial distribution of ionic species within DEDM discharges is determined with support of emission spectra simulations. Spatially-resolved OES reported by Kojima et al. [61] provides some indications on the presence of an electron temperature profile and an inhomogeneous distribution of ionic species under different ionization stages within DEDM discharges performed in air as dielectric; however, the spatial distribution of ionic species reported by them was qualitatively estimated.

The DEDM discharges investigated here are performed with a copper point cathode and an aluminium plane-type anode. Assuming that the DEDM plasma has a Maxwellian electron energy distribution, the fractions of ionic species are estimated by PrismSPECT considering the division of the plasma in three distinct regions, as previously shown in Fig. 5.11. The estimated fractions of ionic species of regions 1, 2 and 3 of the plasma are presented in Fig. 5.21a, Fig. 5.21b and Fig. 5.22 respectively. According to the emission spectra simulations, regions 1 and 2 are almost completely dominated by Al II species during the entire discharge duration.
High Al I spectral lines can be observed in the optical emission spectra of the analysed DEDM discharge; nonetheless, the proportion of Al I species in the plasma is estimated to be below 2%. Furthermore, this is an indication that the DEDM plasma is highly ionized. Highly ionized plasmas were also suggested to exist in EDM discharges in liquid dielectric media by Descoeudres [23]. High Al I lines emission occurs due to the strong rise in electron density by metallic species ionization and due to the proportionally high population densities of the first excited levels within the plasma, as described by Cressault et al. [20].

Fig. 5.21: Fraction of ionic species of plasma assuming LTE: (a) Region 1; (b) Region 2; Copper point cathode and aluminium plane-type anode; $I = 20 A; U_{\text{open}} = 250 V$.

Differently than regions 1 and 2, the central and hottest region of the plasma (region 3) is mostly dominated by Al III species, as can be seen in Fig. 5.22. Even Al IV species are observed at the beginning of the discharge, with about 12% of the plasma composition. The
Al II species increase in proportion probably due to the metal vapour rise, which emanates from the hot anode spot. This result is in accordance with the time-resolved spectroscopic measurements reported by Bacon [6], who infers that the most prevalent ions near the anode spot are Al III and Al IV in HAVA discharges.

Analysis of the fractions of ionic species within the DEDM plasma is also performed in the present work assuming the formation of an electron beam within the electric discharge. The emission spectra simulations consider the plasma plume and electron beam regions described in Fig. 5.16 and indicate large proportions of Al ionic species in the two different studied regions of the DEDM plasma, as shown in Fig. 5.23a and Fig. 5.23b.

Fig. 5.23: Fraction of ionic species of the analysed DEDM plasma assuming non-LTE: (a) Plasma plume region; (b) Electron beam region; Copper point cathode and aluminium plane-type anode; \( I = 20 \ A; U_{\text{open}} = 250 \ V; t = 316 \ \mu s \).

Highly ionized plasmas in HAVA discharges were also reported by Pfender [98] due to the presence of an electron beam. The inhomogeneous distribution of Al species over the different plasma regions is formed due to the high current density in the anode spot region. This causes intense ionization near the anode spot, as well as electron and ion density gradients within the plasma, as inferred by Bacon et al. [7]. The estimated large proportion of Al III species in region 3, assuming the discharge plasma in LTE, as well as in the electron beam region, assuming the plasma in non-LTE, indicates that a hot anode spot exists with dimensions considerably smaller than the crater dimension, as schematically shown in Fig. 5.24.

Al III emission lines are theoretically present in the optical emission spectra of DEDM plasmas, assuming LTE or non-LTE. Therefore, despite the new insight given by emission spectra simulations into the DEDM discharge, it is not possible yet to clarify if there is a temperature profile peaking at the plasma centre or an electron beam formed within the discharge. In order to decide for one of these two hypotheses, additional investigation performed with spatially-resolved optical emission spectroscopy together with the Abel
inversion is necessary. This method and its limitations within the scope of the present investigation are reported in the section 5.4.2.

![Crater profile diagram with ionic species distribution](image)

Fig. 5.24: Distribution of ionic species compared with a crater profile; Copper point cathode and aluminium plane-type anode; \( I = 20 \ A; U_{\text{Open}} = 250 \ V; t = 316 \ \mu s \).

### 5.4. Electron density

#### 5.4.1. Time-resolved electron density

The electron density of DEDM discharges performed with copper point cathode and aluminium plane-type anode is investigated in the present section. Emission spectra simulations are presented as an effective tool to estimate the spatial distribution of the electron density of DEDM plasmas.

Electron density values of the studied DEDM plasma are calculated from the FWHM of the \( \text{H}_\alpha \) emission line (656.28 nm wavelength) according to the theories of Gigosos et al. [33], as described in section 4.6.2. Moreover, the electron densities reported here are calculated from an average of several discharges with a confidence interval of 95%. The \( \text{H}_\alpha \) emission line is acquired and obtained from the integration of the whole radiance profile, which is shown in Fig. 4.15. Thus, the electron density calculation is an average obtained from different regions of the plasma with distinct properties.

Electric current and electron density of the DEDM discharge seems to have similar time behaviour, as can be observed in Fig. 5.25. Both electron density and electric current rise during around 150 \( \mu s \) after the discharge ignition and become relatively stable afterwards, when a slope-shaped current pulse is applied. In contrast, in the case of square-shaped current pulse, the electron density stays relatively constant during the entire DEDM discharge duration. These results agree with the statement of Goldsmith [34], who infers that the electron density follows the time behaviour of the electric current density in a vacuum discharge plasma.

Some indications on the electron densities of different regions of the plasma are estimated by PrismSPECT, shown in Fig. 5.26. The electron density is calculated from given atom and ion densities and the average charge state of the studied plasma regions, as
described in detail by Chung et al. [19]. The atom and ion densities of the DEDM plasma are determined in the present work from the fit between the height and broadening of experimental and simulated $H_\alpha$ emission lines, as previously described in section 4.5.3.

Fig. 5.25: Time-resolved electron density and electric current of DEDM discharges performed with slope and square-shaped electric current pulses; Copper point cathode and aluminium plane-type anode; $I = 20\, A; U_{\text{open}} = 250\, V; t = 316\, \mu s$.

Fig. 5.26: Time-resolved electron density profile of a DEDM discharge performed with square-shaped electric current pulse; Copper point cathode and aluminium plane-type anode; $I = 20\, A; U_{\text{open}} = 250\, V; t = 316\, \mu s$. 

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As presented in Fig. 5.26, emission spectra simulations suggest that the electron density is considerably higher in the hot spot region, if compared with the electron density of the plasma plume region. These electron density results are supported by the observations of discharges in large gaps reported by Pfender [98], which indicate that the geometrical constriction of the discharge causes a higher current density near the hot spot than in the unconstricted plasma column.

### 5.4.2. Spatially-resolved electron density and Abel inversion

Spatially-resolved optical emission spectroscopy analysis applying the Abel inversion can provide properties of specific regions of electric discharge plasmas. Thus, this technique is also used in the present work in order to estimate the electron density profile of the studied DEDM plasma. Spatially-resolved OES processed by the Abel inversion applying the Nestor-Olsen fitting method are explained in detail in section 4.5.2.

Light of the DEDM plasma is acquired and distributed by an optical system over a row of several optical fibres. A small amount of light is collected by each fibre, which hampers the achievement of a high signal-to-noise ratio of the optical emission spectrum for short acquisition times. Therefore, the light of the DEDM plasma is acquired just once during the whole discharge duration, which allows collecting enough light intensity for the spatially-resolved optical emission spectra generation. Although this procedure is able to provide optical emission spectra with proper intensity for the spatially-resolved DEDM plasma investigation, the temporal properties of the electric discharges cannot be analysed. An example of spatially-resolved optical emission spectra, acquired by the sensor of the high-speed camera during optical emission spectroscopy experiments, is presented in Fig. 5.27.

![Spatially-resolved plasma emission spectra](image)

**Fig. 5.27:** Spatially-resolved plasma emission spectra of a DEDM discharge performed with slope-shaped electric current pulse; Copper point cathode and aluminium plane-type anode; \( I = 20 \text{ A}; U_{\text{Open}} = 250 \text{ V}; t = 316 \mu\text{s} \).

The electron density profile of the DEDM plasma is calculated from the \( \text{H}_\alpha \) emission line intensity and broadening according to the theories of Gigosos et al. [33], as described in section 4.4.2. The electron density profile is estimated from the original spatially-resolved optical emission spectra, which is generated from the light collected by each individual fibre.
Thus, the original spatially-resolved optical emission spectra results from the integration the plasma light along the line of sight given by each fibre of the row. In addition, the density profile is also calculated from the spatially-resolved emission spectra processed by the Abel inversion and Nestor-Olsen method. Fig. 5.28 presents the spatially-resolved Hα emission line before and after the Abel inversion application.

Fig. 5.28: Spatially-resolved Hα spectral line of a DEDM discharge performed with slope-shaped electric current pulse and processed by the Abel inversion; Copper point cathode and aluminium plane-type anode; \( I = 20 \, A \); \( U_{\text{open}} = 250 \, V \); \( t = 316 \, \mu s \).

The estimated electron density profile of the analysed DEDM plasma is presented in Fig. 5.29, which shows that the electron density is higher in the centre of the plasma when compared with the electron density values closer to the plasma shell. Since the Abel inversion can just be applied assuming symmetry of the plasma, only the discharges with symmetric density profiles were selected for the calculations reported in Fig. 5.29, corresponding to approximately 50% of the experiments. In a further investigation, DEDM plasmas with asymmetric properties could be analysed by tomographic OES.

The electron density profile calculated from the broadening of the Hα emission line with the Abel inversion agrees with the time and spatially-resolved electron density calculations provided by emission spectra simulations, previously shown in Fig. 5.26. The estimated electron density profile supports the thesis that a HAVA is formed in the investigated DEDM discharges. As described by Boxman et al. [14], the coupling between the electron distribution within the plasma and the magnetic field can lead to a geometric constriction of the discharge, which concentrates the energy flux to the anode and leads to the formation of a hot spot.

Analysis of metallic lines emitted from distinct regions of the plasma can provide indications on different plasma properties, such as density of atoms and ions, distribution of
ionic species and electron temperature profiles. In principle, as mentioned in section 5.3, even the characterization of a non-Maxwellian electron energy distribution can be obtained from spatially-resolved OES with the support of emission spectra simulations.

Small differences between the intensity of metallic lines emitted from distinct regions of the plasma are observed with the used experimental setup. In order to perform the plasma diagnostics with the support of emission spectra simulations, the observed metallic lines need further Abel inversion processing, which requires a high spectral resolution of the studied lines. In contrast with the H\textalpha{} line, which leads to a high spectral resolution due to the Stark broadening (≤ 20 data points), the spectral resolution of the metallic lines measured with the used experimental setup (≤ 5 data points per line) is not enough for a reliable smoothing by the Lorentz distribution, which is crucial for the Abel inversion. Therefore, an experimental setup that provides higher spectral resolution of the metallic lines is required for more advanced plasma diagnostics.

Fig. 5.29: Spatially-resolved electron density profile of a DEDM discharge performed with slope-shaped current pulse and processed by the Abel inversion; Copper point cathode and aluminium plane-type anode; \(I = 20\, A\); \(U_{\text{open}} = 250\, V\); \(t = 316\, \mu s\).
6. **Effects of Important Processing Parameters**

In the present chapter, a parametric study of DEDM plasmas is made applying the advanced optical diagnostics developed in the previous chapters. This investigation covers an analysis of DEDM discharges with different electric currents, electrode geometries, electrode materials and polarities. In addition, a comparison between electric discharges performed in gaseous and liquid dielectric media is also presented.

6.1. **Effects of electric discharge current**

The electric current can affect different DEDM plasma properties. The electron density follows the time behaviour of the electric current, as shown in Fig. 5.25. High-speed imaging measurements indicate that the DEDM plasma plume reaches its maximum dimension already during the first microseconds after the discharge ignition, once square-shaped current pulses are used for the discharges. This behaviour can be observed for all investigated electric currents $I = 10, 20$ and $40 \, \text{A}$, as listed in Table 1. Moreover, higher currents lead to larger plasma plume dimensions, which are estimated here from an average of several discharges with a 95% confidence interval, as shown in the graph of Fig. 6.1.

![Graph showing the dependence of the average plasma expansion on the electric current](image)

**Fig. 6.1:** Dependence of the average plasma expansion on the electric current; Square-shaped current pulses; $U_{\text{open}} = 250 \, \text{V}$; $t = 316 \, \mu\text{s}$.

The discharge plasma expansion measurements presented here are in agreement with the plasma diameter measurements of discharges performed in air as dielectric reported by
Kojima et al. [61], which show similar behaviour for discharges in air under a plane-to-plane electrode geometry configuration.

As reported in section 5.2, optical emission spectra of DEDM discharges performed with copper point cathode and aluminium plane-type anode can only be explained assuming two possible hypotheses:

- Presence of a temperature profile peaking at the plasma centre;
- Formation of an electron beam within the discharge.

DEDM plasma properties are estimated in the present section considering the second mentioned hypothesis. The anode fall can be assumed to correspond to the ionization energy of the anode material, $V_a = 5.986 \, eV$, as previously explained in section 5.2.3 for discharges performed with copper point cathode and aluminium plane-type anode. Furthermore, a hot anode spot with diameter $80 \, \mu m$ is assumed to be formed in the studied DEDM discharges, as described in section 5.2. According to the emission spectra simulations, the electron temperature of the analysed DEDM plasma does not significantly depend on the applied electric current and just slightly varies during the time, as presented in Fig. 6.2.

![Fig. 6.2: Electron temperature for different currents; Copper point cathode and aluminium plane-type anode; Square-shaped current pulses; $U_{open} = 250 \, V; t = 316 \, \mu s$.](image)

Fig. 6.3 shows that the fraction of high-energy electrons within the plasma is noticeably smaller for discharges performed with a current $I = 10 \, A$, if compared with discharges that apply $I = 20$ and $40 \, A$. Since the same hot spot diameter is assumed for all the emission spectra simulations reported in the present section, the estimated fraction of high-energy electrons might indicate that the hot spots of discharges performed with current $I = 10 \, A$ must have smaller dimensions than the ones of discharges performed with $I = 20$ and $40 \, A$. 
This hypothesis is supported by crater measurements shown by Kanmani Subbu et al. [117] for DEDM performed with different discharge energies.

![Graph showing fraction of high-energy electrons for different electric currents](image)

**Fig. 6.3:** Fraction of high-energy electrons for different electric currents; Copper point cathode and aluminium plane-type anode; Square-shaped current pulses; $U_{open} = 250 \, V$; $t = 316 \, \mu s$.

The proportion of the DEDM plasma components are also estimated by emission spectra simulations, which suggest that aluminium and hydrogen fractions of the plasma of discharges performed with point copper cathode and plane-type aluminium anode stay stable during the time for $I = 10 \, A$. In contrast, the hydrogen fraction of the plasma rises and aluminium fraction drops for $I = 20$ and $40 \, A$. This is indicated by the arrow in Fig. 6.4, which represents increasing discharge duration. Furthermore, similar correlation between aluminium and hydrogen is observed for discharges applying copper as cathode under the point-to-point electrode geometry configuration and electric current $I = 20 \, A$. The time behaviour of the hydrogen and aluminium fractions of the electric discharge plasma obtained for different electric currents can be observed more in detail in Fig. 6.5a and Fig. 6.5b respectively.

The aluminium fraction decreases and the hydrogen fraction rises during the development of discharges performed applying different electric currents with copper point-type cathode. These composition observations might be explained by the plasma analysis reported by Kharin [56], who infers that strong anode metal evaporation takes place during the start of a HAVA, followed by an erosion gap enlargement and metal evaporation cooling effect. These phenomena can lead to a drop in the anode spot temperature and metal evaporation, which could be a possible reason for the reduction of the aluminium fraction of the plasma composition during the discharge development.
Fig. 6.4: Correlation between Al and H fractions of the plasma; Copper point cathode; aluminium point and plane-type anode; Square-shaped electric currents; $U_{open} = 250 \text{ V}$; $t = 316 \mu\text{s}$.

Fig. 6.5: Time behaviour of the fractions of components of the plasma for different electric currents: (a) Hydrogen; (b) Aluminium; Copper point cathode and aluminium plane-type anode; Square-shaped electric currents; $U_{open} = 250 \text{ V}$; $t = 316 \mu\text{s}$.

Depth measurements of craters left by DEDM discharges with different pulse durations might support the stated hypothesis concerning erosion gap enlargement. The analysed craters were formed by single discharges applying copper point cathode and plane-type anode. The plane-type anode surface was machined by diamond fly-cutting before the single discharge experiments. Fig. 6.6 and Fig. 6.7 show examples of craters left by single DEDM discharges performed with pulse durations $t = 4.9 \mu\text{s}$ and $75 \mu\text{s}$ respectively.
Effects of important processing parameters

Fig. 6.6: Crater left by a single discharge performed with pulse duration $t = 4.9 \mu s$; Copper point cathode and plane-type anode; $U_{open} = 250 V$; $I = 20 A$, slope-shaped electric current.

Fig. 6.7: Crater left by a single discharge performed with pulse duration $t = 75 \mu s$; Copper point cathode and plane-type anode; $U_{open} = 250 V$; $I = 20 A$, slope-shaped electric current.

The graph of Fig. 6.8 presents the dependence between the crater depth and the electric discharge pulse duration with 95% confidence interval. This graph indicates a crater depth peak between the 50 $\mu$s and 100 $\mu$s of the discharge after the ignition, becoming relatively stable afterwards. As stated in section 2.3, longer electric discharge pulses can lead
to larger material removal; nonetheless, according to Takezawa et al. [120], the relation between the volume of material removed from the crater and its resolidified layer is considerably smaller for longer pulses due to an inefficient material ejection mechanism. In addition, the observations reported here are also supported by the EDM experimental results presented by Klocke [60]. Measurements of the volume of material removed from the craters by single electric discharges performed with different pulse durations could provide indications on the evolution of the metal evaporation during the time; nevertheless, this association would also need to consider the material removed from the craters in the form of debris.

As crater measurements reported by Kanmani Subbu et al. [117] suggest, the stable proportions of aluminium and hydrogen components of the plasma of discharges performed with $I = 10 \, A$ might be explained by the small anode spot formed, when compared with the ones generated by $I = 20$ and $40 \, A$. This could lead to smaller absolute metal evaporation and gap enlargement, which are the reasons presented by Kharin [56] for the anode spot temperature reduction; however, it is important to state that additional investigation is still necessary in order to properly explain the reported correlations between hydrogen and aluminium fractions of the plasma in DEDM.

![Figure 6.8: Depth of craters left by electric discharges performed with different pulse durations; Copper point cathode and plane-type anode; $U_{\text{open}} = 250 \, V$; $I = 20 \, A$, slope-shaped electric current.](image)

**6.2. Effects of electrode material, geometry and polarity**

The material, polarity and geometry of the applied electrodes play an important role in DC discharges. Thus, the DEDM discharges investigated in the present section are performed with different electrode geometries and materials. Several important plasma parameters are shown and described here. Afterwards, a discussion involving interpretation of the results is presented.

Emission spectra simulations indicate a slight increase of the electron temperature of DEDM discharges performed with point-type aluminium cathode and copper anode, as emphasized with a round marker in a curve of Fig. 6.9.
The electron density of the DEDM discharges also increases when performed with copper anode and aluminium cathode under the point-to-point electrode geometry configuration, as highlighted with a round marker in Fig. 6.10. Furthermore, the point-to-plane electrode geometry configuration leads to larger electron densities than the point-to-point one. The electron temperature and density are quite stable for the other applied electrode geometry configurations and polarities.

Fig. 6.9: Electron temperature of electric discharges performed with different electrode polarities and geometries; $U_{\text{open}} = 250 \, V$; $t = 316 \, \mu s$; Square-shaped pulses, $I = 20 \, A$.

Fig. 6.10: Electron density of discharges performed with different electrode geometries and polarities; $U_{\text{open}} = 250 \, V$; $t = 316 \, \mu s$; Square-shaped current pulses, $I = 20 \, A$. 
Electric discharges performed using a point-type aluminium anode have a plasma expansion almost two times larger than discharges that apply a plane-type aluminium anode, as presented in Fig. 6.1. In contrast, the plasma expansion of discharges performed with copper as anode reaches values just slightly different for both used electrode geometry configurations under the same electrical parameter set.

In terms of composition, emission spectra simulations indicate that the anode material dominates the discharges performed between point-type electrodes, as shown in Fig. 6.11a and Fig. 6.11b. This plasma property is observed independently of the applied electrode materials and anode electrode geometry. In addition, the fraction of cathode material in the plasma reaches its maximum value immediately after the discharge ignition for both electrode polarities, dropping afterwards. Since a HAVA discharge starts burning on the cathode side, as described by Miller [88], these observed characteristics are one more indication that discharges similar to anode dominated vacuum arcs are formed under the studied DEDM processing conditions.

The fraction of the copper point-type cathode material in the plasma for electric discharges performed under the point-to-point geometry configuration, presented in Fig. 6.11b has a time behaviour similar to the point-to-plane one, shown in Fig. 6.12a. However, a smaller fraction of copper cathode material is observed under the point-to-plane configuration.

The plasma composition of discharges performed with currents $I = 20 \, \text{A}$ is very similar to the ones of discharges performed with $I = 10$ and $40 \, \text{A}$ under the same working conditions. Furthermore, a significant fraction of the plasma is composed of hydrogen, which varies in time between 15% and 30% for both electrode polarities using the point-to-point electrode geometry configuration.
Emission spectra simulations suggest that a point-type cathode concentrates the discharge to the anode spot in DEDM. As explained by Boxman et al. [14], the anode spot becomes an intense source of metal vapour, which sustains a HAVA discharge. Moreover, application of a point-type aluminium anode leads to discharge plasmas with larger expansion, lower electron density and electron temperature than discharges performed with a plane-type aluminium anode electrode. The point-type anode allows the discharge to be concentrated to a relatively small region, which increases the anode material erosion and evaporation.

The observed increase of electron temperature and density of the plasma of discharges performed with aluminium point-type cathode might be associated with the considerable changes in plasma composition, which take place simultaneously. High fraction of the aluminium point-type cathode is present in the plasma during the beginning of the discharge, which progressively becomes dominated by the copper anode material, as shown in Fig. 6.11a. This observation can also be explained by the characteristics of a HAVA, since this type of discharge starts burning in the cathode material, as described by Miller [88].

The plasma of discharges performed with aluminium point-type cathode has smaller dimension, larger fraction of the cathode material and increasing electron density and temperature, when compared with discharges made with copper point-type cathode. These observations agree with the tool wear analysis reported by Tsai et al. [128], who infer that larger fraction of the aluminium point-type cathode is eroded by the discharge than the copper point-type one, since aluminium has lower melting and evaporation points and lower electrical and thermal conductivities than copper.

The plasma composition of electric discharges performed with copper point anode and aluminium plane-type cathode can reach copper fractions of around 20%. This observation
indicates that an aluminium plane-type cathode does not lead to an anode dominated discharge, since its plasma is mainly formed of components originated from the cathode material, as shown in Fig. 6.12b. In addition, this observation supports the thesis that a point-type cathode is necessary for concentrating the discharge to the anode spot.

A clear correlation between the copper and aluminium fractions of the plasma is also observed in discharges performed with point-type copper anode and aluminium cathode. The copper anode fraction of the plasma increases, while the aluminium cathode fraction decreases. This can be observed for increasing times into the discharge as the arrows in Fig. 6.13 indicate. This time-dependent correlation suggests a transition from the diffuse mode of the discharge starting at the cathode to a more stable anodic vacuum arc, as explained by Miller [89]. Moreover, no significant correlation between the copper and aluminium fractions of the plasma are observed for discharges with point-type copper cathode and aluminium anode, as well as for both polarities of discharges with the point-to-plane electrode configuration, as the arrows of in Fig. 6.13 indicate.

![Fig. 6.13: Correlation between the copper and aluminium fractions of the electric discharge plasma in air; $U_{open} = 250 V$; $t = 316 \mu s$; Square-shaped currents, $I = 20 A$.](image)

6.3. Effects of dielectric medium

The properties of discharge plasmas can be drastically affected by the used dielectric medium. Different electrical breakdown, discharge plasma and post-discharge properties have been reported in the literature [23, 53, 61, 83] depending on the applied dielectric. Nevertheless, some researchers in the field of EDM [61, 93, 94] assume that discharges in gas and liquid dielectric media have very similar plasmas. Since the EDM discharge is formed within a gas bubble in liquid, those authors infer that discharges in gas and liquid should have quite the same properties. This hypothesis is checked in the present section, which reports on a comparison between EDM discharges performed in liquid and in gaseous dielectric media. The
discharges analysed in the present section are performed with square-shaped electric current $I = 20 \, A$ using copper point and aluminium plane-type electrodes in oil and in air as dielectric media.

Large plasma plume and strong light emission is detected by high-speed imaging immediately after the ignition of EDM discharges in oil dielectric. This phenomenon was also observed by Descoeudres [23], who performed high-speed imaging of EDM discharges in liquid dielectric media. Normalization of the plasma light intensity acquired by his high-speed imaging experiments indicates that the dimension of EDM plasmas in liquid just slightly varies during the whole pulse duration. Therefore, the plasma dimension of EDM discharges in oil can be considered fairly constant during the time, around $500 \, \mu m$. Furthermore, in addition to the plasma plume, electric discharges performed in oil are surrounded by a gas bubble, as previously shown in Fig. 4.6. High-speed imaging also indicates that electric discharges performed with a point-type copper anode in air dielectric have a plasma plume that reaches a dimension of $540 \, \mu m$, whereas a dimension of $400 \, \mu m$ is registered when a point-type cathode is applied. The time-dependent plasma and bubble expansions of discharges in air and oil as dielectric are shown in Fig. 6.14.

![Graph of plasma and bubble expansion](image)

**Fig. 6.14:** High-speed imaging of electric discharge plasmas in air and oil dielectric media and gas bubble; $U_{open} = 250 \, V$; $t = 316 \, \mu s$; Square-shaped currents, $I = 20 \, A$.

The material removal and generation of craters on the workpiece material in EDM in liquid can be affected by the dynamics of the gas bubble formed around the discharges, as
reported by Zhang et al. [141]. The measurements presented in Fig. 6.14 show that the gas bubble dimension reaches its maximum values between 2,500 and 4,500 \( \mu m \). In addition, bubbles that achieve maximum dimensions below 2,500 \( \mu m \) collapse even before the discharge pulse is interrupted, as shown in Fig. 6.15. Similar observations were reported by Maradia et al. [84] for discharges performed in the microsecond scale, whereas Kanemaru et al. [52] presented also comparable bubble behaviour for capacitive EDM electric discharges.

Fig. 6.15: Discharge plasma and collapsed gas bubble in oil

Properties of the discharge plasmas in oil are also estimated in the present work by emission spectra simulations according to the procedure described in section 4.5.3 and the assumptions presented in section 5.2.2. Fig. 6.16 shows a fit between a typical optical emission spectrum of a discharge in oil and the synthetic spectrum simulated by PrismSPECT. As can be observed in Fig. 6.16, some of the grouped lines in the optical emission spectrum, between 400 nm and 550 nm wavelengths, are probably molecular bands which cannot be simulated by this software.

Fig. 6.16: Experimental and simulated spectrum for copper point anode and aluminium plane-type cathode in oil dielectric at the 145 \( \mu s \) after the discharge ignition; \( U_{open} = 250 \, V \); Square-shaped currents, \( I = 20 \, A \).
Descoeudres [23] infers that EDM discharges in oil have cold plasmas and are in LTE. In order to compare the discharges in gaseous and liquid dielectric media, the hypothesis of plasmas in LTE is also adopted for the discharges studied here. Emission spectra simulations indicate that the plasma of electric discharges performed in oil must have a temperature profile, as also observed for the discharge in air as dielectric. The electron temperature estimations for both dielectric media are shown in Fig. 6.17.

Fig. 6.17: Electron temperature of the plasma for different electrode polarities and dielectric media: (a) Copper point anode and aluminium plane-type cathode; (b) Copper point cathode and aluminium plane-type anode; $U_{\text{open}} = 250 \, V$; $t = 316 \, \mu s$; Square-shaped currents, $I = 20 \, A$. 
The observed spectral lines of discharges in oil cannot be emitted by plasmas with a spatially constant electron temperature, as also reported for discharges in air in section 5.2.2. In order to compare the observed and simulated emission spectra, a simplified temperature profile is adopted here, assuming two temperature regions. The EDM plasma diameter is separated in a region of higher electron temperature at its centre, which might be compatible with the formation of a hot spot, and a region of lower electron temperature, defined between the hotter centre and the measured shell diameter of the plasma.

The hot spot region of the plasma in both dielectric media is assumed to have a diameter Ø 80 μm, as proposed in section 5.2.2 for discharges in air. The dimension of the colder region of the plasma is calculated subtracting the diameter of the hot spot region from the plasma plume diameter, measured by high-speed imaging and shown in Fig. 6.14. In addition, the atom and ion densities of the plasma are assumed to be constant over the plasma cross-section. Since the optical emission spectra are obtained by summing light emitted from distinct regions of the plasma, one can assume for simplification that the different components of the plasma composition are homogeneously distributed.

According to the emission spectra simulations, the average electron temperature of discharges in air and oil dielectric media reach similar values of around 15,000 K (~1.29 eV) in the plasma plume, and about 21,000 K (~1.81 eV) in the hot spot region during their development in all studied conditions, as presented in Fig. 6.17. Despite this similarity, different electron temperature time behaviour is observed. The temperature of discharges in liquid slightly follows the time behaviour of the gas bubble formed around the plasma. This observation agrees with the electron temperature calculations of electric discharges in oil reported by Descoeudres [23], applying the two-line method. In contrast, electron temperatures of discharges performed in air with a point anode are fairly constant, while the temperatures of discharges with point-type cathode have a reduction during the time.

The optical emission spectra of electric discharges performed in oil have emission lines with very large broadening during the first 20 µs after the ignition, drastically decreasing during the development of the discharge. Furthermore, large continuum can be observed in the emission spectrum at the beginning of the discharge, which also drops during the time, as presented in Fig. 6.18. These characteristics are not observed in OES of discharges in air. The electron density of the different analysed regions of the plasma is calculated by PrismSPECT considering the estimated atom and ion densities and plasma mean charge, as described in section 4.5.3.

Emission spectra simulations indicate that the electron densities of the plasma of discharges in oil reach values up to 8 times higher than the plasma of discharges in air during its first few microseconds. These electron density calculations, presented in Fig. 6.19, are in agreement with the results reported by Descoeudres [23]. According to his analysis, EDM plasmas overcome an extreme pressure imposed by the liquid dielectric in the very beginning of the discharge, leading to very high plasma densities, around \(2 \times 10^{18} \text{ cm}^{-3}\). The high electron density achieved immediately after the discharge ignition is probably the main reason
for the broadening and merging of Al II lines (623.1 nm and 624.3 nm wavelengths) reported in Fig. 6.18.

![Spectrum of Al II and Hα lines](image)

**Fig. 6.18**: Al II and Hα lines of a discharge performed with copper anode and aluminium cathode in oil dielectric; $U_{open} = 250 \, V; \, t = 316 \, \mu s; \text{ Square-shaped currents, } I = 20 \, A$.

The electron density drops considerably during the development of the discharges in oil, becoming up to 5 times lower than the ones observed for electric discharges in air. This electron density reduction is in agreement with the investigation reported by Kanemaru et al. [52], who infer that the time behaviour of the pressure and dynamics of the gas bubble formed around the plasma channel is correlated with the electron density.

Since the electric discharges in air are performed in atmospheric pressure, changes in their plasma properties must be related only to the used electrode material, electrode geometry and adopted electrical parameter set. Electric discharges in air have quite stable electron density time behaviour, as one can observe in Fig. 6.19.

The composition of the EDM discharge plasmas can be substantially different depending on the applied dielectric medium, as emission spectra simulations suggest. DEDM discharges are dominated by metallic material from the electrode, as presented in Fig. 6.11 and Fig. 6.12. Components of the dielectric, such as nitrogen and oxygen, are not significantly present in the plasma. As described in section 5.1.2, this is explained by the properties of a HAVA, which has the anode material as its main source of plasma composition.

In contrast to the discharges in air as dielectric, emission spectra simulations indicate that discharges in oil are mostly composed of hydrogen and carbon with some metallic contamination from the electrodes, as presented in Fig. 6.20 concerning both electrode
polarities. Thus, electric discharges performed in oil have most of their composition originated from the cracking of highly linked hydrocarbons of the dielectric.

Fig. 6.19: Density of electrons of the plasma for different electrode polarities and dielectric media; $U_{\text{open}} = 250 \, V$; $t = 316 \, \mu s$; Square-shaped currents, $I = 20 \, A$.

High variation of carbon and hydrogen contents of the plasma is observed during the time for discharges in oil, whereas the proportion of metallic components just slightly decreases. The new insight into the EDM plasma of electric discharges in oil given by emission spectra simulations contradicts other researchers [23, 84], who deduced an increase of
metallic composition of the plasma in oil dielectric based on observations of rising metallic lines normalized to the $H\alpha$ line. This contradiction can be explained by two reasons:

- Constant $H\alpha$ line intensity during the time is assumed by the cited authors in order to compare it with metallic spectral lines; however, emission spectra simulations indicate that the $H\alpha$ line intensity is considerably affected by the ionization of hydrogen in the plasma. Therefore, the $H\alpha$ line cannot be assumed to be constant during the discharge development;

- Emission spectra simulations show that the proportion of metallic ionic species considerably change during the discharge. Since the intensity of the metallic lines is also associated with the plasma ionization, an increase of some specific metallic lines does not necessarily mean that a larger fraction of metallic components is present within the plasma.

![Fig. 6.20: Fraction of plasma components of an electric discharge in oil dielectric: (a) Copper point anode and aluminium plane-type cathode; (b) Copper point cathode and aluminium plane-type anode; $U_{\text{open}} = 250\ V$; $t = 316\ \mu s$; Square-shaped currents, $I = 20\ A$.](image)

High fraction of aluminium is observed in the plasma composition of discharges in air and oil dielectric media. This probably occurs due to the low melting and evaporation points of this material. Erosion of a workpiece material with higher melting and evaporation points could lead to a lower fraction of its material in the plasma composition. This hypothesis can be properly verified by a further investigation, using OES supported by emission spectra simulations. Moreover, OES was already presented by Kunieda et al. [65] as a promising tool for investigating the wear ratio and its mechanisms in EDM. The method of advanced plasma analysis proposed in the present work can be used to give even more information about the tool wear mechanisms by estimating several plasma properties of EDM discharges.

As described in section 4.5.2, the optical depth is a very important property of the plasma for OES, since optical emission lines can be self-absorbed within the plasma channel.
The DEDM plasmas studied in the present work are optically thin, as previously reported in section 5.2.2. Therefore, self-absorption of the plasma light can be neglected for the optical emission spectra analysis. In the present section, the optical depth of EDM plasmas in oil is investigated.

The optical depth of a EDM plasma in oil is simulated by PrismSPECT assuming a discharge with 540 $\mu$m diameter, $T_e = 15,000\ K\ (\sim 1.29\ eV)$ and $N_e = 6 \cdot 10^{17}\ cm^{-3}$, while the fractions of plasma components are $H_{fr} = 0.6; Al_{fr} = 0.25; Cu_{fr} = 0.1; C_{fr} = 0.05$ for hydrogen, aluminium, copper and carbon respectively. The simulation of the optical depth of the EDM plasma in oil indicates that the Al I lines are optically thick ($\tau > 1$), so self-absorption needs to be considered for the optical emission spectra analysis. Since PrismSPECT automatically considers the light absorption of optically thick emission lines, the plasma parameters reported in the present work have the self-absorption effects already included in the simulations.

![Optical depth simulation of a plasma with 540 $\mu$m diameter in oil as dielectric; $T_e = 15,000\ K; N_e = 6 \cdot 10^{17}\ cm^{-3}; H_{fr} = 0.6; Al_{fr} = 0.25; Cu_{fr} = 0.1; C_{fr} = 0.05$.](image)

**Fig. 6.21:** Optical depth simulation of a plasma with 540 $\mu$m diameter in oil as dielectric; $T_e = 15,000\ K; N_e = 6 \cdot 10^{17}\ cm^{-3}; H_{fr} = 0.6; Al_{fr} = 0.25; Cu_{fr} = 0.1; C_{fr} = 0.05$.

6.4. **Summary of the DEDM plasma physical properties**

Important indications on the DEDM discharge properties, achieved by advanced plasma diagnostics, as well as the effects of different processing parameters on the discharge physics, are summarized in the following sections.

6.4.1. **DEDM plasmas diagnostics**

DEDM is commonly performed with a point-type tool cathode due to the relatively high material removal and very low tool wear obtained, as mentioned in chapter 1. Therefore, the
DEDM plasma properties of electric discharges performed with a copper point cathode and an aluminium plane-type anode under the electrical parameter set $I = 20 \, A$ and $U_{\text{open}} = 250 \, V$ are briefly described in the following topics:

- Determination of the DEDM plasma composition given by emission spectra simulations indicate that the plasma starts burning on the point cathode material immediately after the electrical breakdown. During the development of the DEDM discharge, the plasma becomes dominated by the anode material. In contrast, electric discharges performed with point anode and plane-type cathode have large fractions of both electrodes’ material in the plasma;

- Electron temperature calculations by the two-line Boltzmann method suggests that the plasma of DEDM discharges are cold. Assuming a single electron temperature, it should vary around $17,000 \, K \ (\approx 1.46 \, eV)$;

- Emission spectra simulations reveal that the optical emission spectra of DEDM plasmas cannot be fully explained with a spatially constant electron temperature. These simulations show that the plasmas must either have an electron temperature profile or an electron beam within the discharge;

- Assuming a Maxwellian electron energy distribution, the electron temperature profile has a peak of around $25,000 \, K \ (\approx 2.15 \, eV)$ at the middle of the plasma during the first $32 \, \mu s$, decreasing to around $20,000 \, K \ (\approx 1.72 \, eV)$ afterwards. The electron temperature of the colder region of the plasma, situated between its hot centre and shell, is around $14,000 \, K \ (\approx 1.21 \, eV)$ and slightly decreases during the time;

- Assuming a non-Maxwellian electron energy distribution, such as an electron beam, the electron temperature of the plasma plume varies around $14,000 \, K$, whereas $20\%$ of the electrons in the central region of the plasma are accelerated towards the anode during the first $32 \, \mu s$, decreasing below $10\%$ as the electric discharge develops further;

- Electrical parameter measurements suggest that the DEDM discharge starts in the diffuse mode, changing during the time towards an anodic vacuum arc. These indications are supported by OES. Assuming plasmas in LTE, a decrease in the electron temperature in the region of the hot spot is identified, whereas considering plasmas in non-LTE, a drop in the fraction of high-energy electrons within the discharge is observed;

- Analysis of the fractions of ionic species of DEDM discharges shows that a region at the centre of the discharges, between three and five times smaller than the plasma dimension, is dominated by $\text{Al} \, \text{III}$ and $\text{Al} \, \text{IV}$ species originated from the anode material, which is compatible with the formation of an anode hot spot;

- The hot anode spot dimensions estimated by emission spectra simulations, between $40$ and $130 \, \mu m$, are considerably smaller than the average crater diameter measured by confocal microscopy, which is around $185 \, \mu m$;
Effects of important processing parameters

- Time-resolved calculations of the electron density from the FWHM of the $H_\alpha$ emission line indicate that this plasma parameter follows the time behaviour of the electric current, which fits to the characteristics of a vacuum arc;
- Spatially-resolved OES processed by the Abel inversion and interpretation of OES supported by emission spectra simulations indicate that the electron density peaks at the plasma centre, which might be associated with a geometrical constriction of the discharge. The plasma in the region of the hot spot reaches electron densities around $1.5 \cdot 10^{17} \text{ cm}^{-3}$, a density value about 80% higher than in the unconstricted plasma column;
- The above-mentioned DEDM plasma properties are very similar the ones of hot anode vacuum arcs (HAVA), where the plane anode and the inter-electrode gap plasma provide most of the energy to the discharge, while the point-type cathode can be considered an inert electrode. These discharge characteristics explain the small tool electrode wear in DEDM, widely reported in the literature.

6.4.2. Effects of different processing conditions

Since the electric discharge conditions can influence the DEDM plasma, the following topics describe the diagnostics of discharges performed with different dielectric media, electrode polarities, materials and geometries:

- The plasma plume of DEDM discharges performed with electric currents $I = 10, 20$ and $40 \text{ A}$ under a copper point cathode and aluminium plane-type anode geometry configuration have electron temperatures fairly constant during the time, around $14,000 \text{ K}$, as emission spectra simulations indicate;
- Assuming a non-Maxwellian electron energy distribution, emission spectra simulations suggest that the fraction of high-energy electrons within the plasma has a peak at the beginning of the discharge for all the above-mentioned electric currents. This relatively high fraction of high-energy electrons is followed by its decrease during the time;
- The fraction of high-energy electrons within the plasma is considerably smaller for discharges performed with $I = 10 \text{ A}$, if compared with discharges performed with $I = 20$ and $40 \text{ A}$. Discharges performed with $I = 10 \text{ A}$ might lead to the formation of smaller hot anode spots. This hypothesis is supported by crater measurements reported in the literature;
- Correlations between hydrogen and aluminium compositions of the plasma indicate a decrease in the aluminium fraction, while the hydrogen fraction increases during the time for discharges performed with $I = 20$ and $40 \text{ A}$. In contrast, this correlation is fairly constant for discharges performed with $I = 10 \text{ A}$. These observations can be related to the effects of anode metal vapour generation and the gap increase due to the anode material erosion, which are strengthened by higher electric currents;
Effects of Important Processing Parameters

- DEDM discharges performed with copper anode and aluminium cathode under the point-to-point electrode geometry configuration have an increase in electron temperature and density of the plasma during the time. The increase of these plasma parameters takes place simultaneously to the changes in plasma composition, indicating the transition of the diffuse mode towards an anodic vacuum arc, which is dominated by the copper anode material;

- The application of a point-type cathode leads to the formation of anode dominated discharges independently of the used electric current, electrode materials and anode geometry, whereas a plane-type cathode does not concentrate the discharge to the anode spot. This suggests that the point-type cathode geometry is crucial for the generation of a discharge similar to a HAVA;

- Plasma composition analysis of electric discharges performed with copper point anode and aluminium plane-type cathode indicates that an aluminium plane-type cathode does not lead to an anode dominated discharge, since its plasma is mainly formed of components originated from the cathode material. This reinforces the thesis that a point-type cathode is necessary for concentrating the discharge to the anode spot;

- A comparison between discharges in air and oil shows that both must have a temperature profile. The electron temperatures reach similar values in the analysed regions for both dielectric media; however, differences in their time behaviour can be observed. The electron temperature of discharges performed in oil slightly follow the time behaviour of the gas bubble formed around the plasma for both electrode polarities. In contrast, the electron temperature has a small decrease for discharges in air with a point cathode, remaining stable for discharges with a point-type anode.

- Emission spectra simulations indicate that discharge plasmas in oil have electron densities up to 8 times higher than discharges in air just after the electrical breakdown. This high electron density can be explained by the pressure imposed by the oil, which is not present in discharges performed in air; however, the electron density of discharges in oil decreases during the development of the discharge as a result of its surrounding bubble expansion, becoming up to 5 times lower than the electron densities of discharges in air;

- Differently than discharge plasmas in air, which have material from the electrodes as their main composition, discharge plasmas in oil are dominated by hydrogen and carbon from the dielectric medium. Some metal contamination from the electrodes is observed in the plasma composition of discharges in oil, which slightly decreases during the time;

- Emission spectra simulations indicate that the EDM plasmas in air studied in the present work are optically thin, whereas some emission lines of EDM plasmas in oil are optically thick. Thus, self-absorption needs to be considered for the analysis of optical emission spectra of electric discharges performed in oil with the working conditions adopted in the present work.
7. DEDM DISCHARGE MODELLING AND SIMULATION

The physics of electric discharge plasma-material interactions has been modelled by several researchers, as summarized in section 2.3.3. In particular, researchers from the Institute of Machine Tools and Manufacturing (IWF) from ETH Zurich have published models of different electrical discharge machining processes, such as spark assisted electrochemical machining (SAEM), die-sinking and wire-EDM.

Krötz [64] proposed a heat transfer model that simulates single craters formed by electrochemical discharges. The heat source is modelled as a disc with homogeneous heat flux distribution, whereas its dimensions are estimated from the analysis of craters left on the workpiece surface. Maradia [83] developed a heat transfer model with an expanding heat source, which simulates eroded craters in die-sinking EDM. Weingärtnert [133] presented a heat transfer model that simulates craters generated in WEDM. This model considers the effects of a moving workpiece electrode on the craters formation, taking into consideration the thermophysical properties of the used material and the melting and evaporation latent heat.

The above-cited simulation models estimate the fraction of energy deposited onto the workpiece electrode from comparisons between craters left on its surface and heat transfer simulation results. This method of power deposition estimation has been used by several authors [25, 96, 107, 136, 137, 141, 142]. The present work proposes a different analysis, from which the workpiece power deposition is calculated using a thermal plasma model and emission spectra simulations. The fractions of the discharge power dissipated by electrical conduction, radiation and convection are calculated by electrical circuit simulations designed with a modified Cassie-Mayr model.

7.1. Anode power deposition

As described in chapter 1, the workpiece electrode is normally set as anode in DEDM, since higher MRR is obtained in comparison with the results achieved with the inverted polarity. The discharge energy is deposited onto the anode material by incident electrons, neutral and excited atoms striking its surface, chemical reactions, Joule heating, heat conduction and radiation, as described by Guile [38]. Furthermore, more than one plasma channel can be formed from a single discharge, leading to the formation of several craters on the anode surface, as can be observed in Fig. 7.1.

As Pfender [98] explains, the heat transfer given by the plasma-material interactions is strongly influenced by the behaviour of the plasma adjacent to the electrodes, in the so-called electrode regions. Electric, magnetic, thermal and fluid dynamics effects are some of the physical phenomena involved in these regions. Thus, an investigation of the energy balance at
the anode, with regard to the particular case of DEDM discharges in air, is developed here by electrical circuit simulations and calculations of the plasma heat flux given by a physical model.

Fig. 7.1: Several craters left by a single electric discharge; copper point and plane-type electrodes; \( U_{\text{open}} = 250 \, V \); \( t = 75 \, \mu s \); Square-shaped currents, \( I = 20 \, A \).

### 7.1.1. Thermal plasma model

Heat transfer given by plasma-material interactions is considerably more complex than the heat transfer phenomena involved between an ordinary gas and a material surface, as described by Pfender [98]. Transient plasma parameters, free electrons and positive ions in the vicinity of the electrode surface and relatively strong radiation fields are involved in the physics of plasma-material interactions. Despite this complexity, Eckert et al. [28] infer that the energy transfer from a thermal plasma to the anode material mostly occur as a function of the following mechanisms:

- Thermal and kinetic energy \( q_j \) of electrons that penetrate the anode surface

\[
q_j = j_e \left( \frac{5 k_B T_e}{2 e} + V_a \right)
\]

where \( e \) is the elementary charge, \( k_B \) is the Boltzmann constant, \( V_a \) is the anode potential fall and \( j_e \) is the electron current density at the anode surface.

- Heat flux \( q_{\phi_a} \) generated by condensation of electrons at the anode surface

\[
q_{\phi_a} = j_e \phi_a
\]

where \( \phi_a \) is the work function of the anode surface. As described by Eckert et al. [28], the work function is proportional to the electron condensation energy, which is released by the electrons from the discharge during their penetration into the electrode surface.
Convective heat transfer $q_{\text{conv}}$ from the plasma to the anode surface

\[ q_{\text{conv}} = h_i (i_e - i_w) \]  \hspace{1cm} (7.3)

where $h_i$ is the heat transfer coefficient, $i_e$ is the stagnation enthalpy of the plasma outside the sheath and $i_w$ is the enthalpy of the plasma in the vicinity of the electrode surface.

Radiative heat transfer $q_{\text{ra}}$ from the plasma to the anode surface

\[ q_{\text{ra}} = \varepsilon \sigma A_s T_e^4 \]  \hspace{1cm} (7.4)

where $A_s$ is the radiating surface area of the plasma and $\sigma$ is the Stefan-Boltzmann constant. The radiation is emitted from electrons that suffer elastic collisions with heavy particles within the plasma.

Baalrud et al. [5] infer that nearly all the atoms are ionized in the anode sheath of a HAVA. This high ionization sharply rises the heat transfer from the plasma to the anode, since the electrical and thermal conductivities of the plasma are governed by the electrons, which have high mobility. As described by Pfender [99], the electric current flow onto the anode surface, given by $q_j$ and $q_{\phi_a}$, dominates the heat transfer effects. As schematically shown in Fig. 7.2, the heat flux $q_a$ from a thermal plasma onto the anode surface can be calculated by an equation that considers (7.1) and (7.2), which is described as

\[ q_a = j_e \left( \frac{5}{2} \frac{k_B T_e}{e} + V_a + \phi_a \right) \]  \hspace{1cm} (7.5)

Fig. 7.2: Heat flux from a HAVA to the anode material, adapted from Eckert et al. [28]

The anode power deposition is calculated with (7.5) applying the work function of the aluminium surface $\phi_a = 4.6 \text{ eV}$ and the electron temperatures of the hot spot region estimated by the emission spectra simulations reported in section 5.2.2. The anode heat flux
calculations assume the formation of a single plasma channel, whereas the energy flows onto a spot area given by $\phi \approx 80 \mu m$ on the anode surface, as previously used for emission spectra simulations in section 5.2.2. The anode power deposition is schematically shown in Fig. 7.3.

![Fig. 7.3: Anode power deposition](image)

Fig. 7.3: Anode power deposition

Fig. 7.4 shows the power calculated by (7.5) and the total discharge power obtained from RMS electric current and burning voltage measurements with a confidence interval of 95%. This result suggests that around 90% of the discharge power flows onto the anode material in DEDM for the applied experimental conditions, which fits to the properties of a HAVA discharge. Miller [88] infers that the anode spot requires high local power densities, which in the case of a HAVA, normally means nearly the total power of the discharge.

![Fig. 7.4: Electric discharge power measured and calculated by the thermal plasma model (7.5) proposed by Pfender [99]; Copper point cathode and aluminium plane-type anode; $U_{\text{open}} = 250 \, V$; $t = 316 \, \mu s$; Slope-shaped currents, $I = 20 \, A$.](image)

Fig. 7.4: Electric discharge power measured and calculated by the thermal plasma model (7.5) proposed by Pfender [99]; Copper point cathode and aluminium plane-type anode; $U_{\text{open}} = 250 \, V$; $t = 316 \, \mu s$; Slope-shaped currents, $I = 20 \, A$. 93


### 7.1.2. Electrical circuit simulations

Electrical properties of arc discharges have been described by the well-known equations from Cassie [17] and Mayr [86] for several applications. The Mayr equation calculates the plasma conductance based on the balance between energy input and thermal conduction, whereas the conductance is governed in the Cassie equation by the balance between energy input and convection.

The Cassie equation is generally applied in high current arc discharge estimations. This equation is particularly suitable for discharges with losses dominated by convection and includes the plasma channel deformation, which is proportional to its cross-sectional area. Furthermore, the electric discharge channel is assumed to be a plasma column with radially homogeneous temperature distribution and constant axial electric field strength. The Cassie equation can be represented as

\[
\frac{1}{G} \frac{dG}{dt} = \frac{1}{\theta_1} \left( \frac{u^2}{V_0^2} - 1 \right) \quad (7.6)
\]

where \( G \) is the discharge arc conductance, \( V_0 \) is the constant discharge voltage in steady state, \( u \) is the instantaneous voltage across the arc and \( \theta_1 \) is the arc time constant, which represents the ratio between total discharge energy and the part of its dissipation by convection.

In contrast, the Mayr equation provides consistent results for low current arc discharges. This equation considers electric discharge energy dissipation by the heat formed from the electric current flow into the electrode material. Furthermore, this physical model includes a radial diffusion at constant rate and assumes an electric discharge plasma channel column with constant radius. The Mayr equation can be written as

\[
\frac{1}{G} \frac{dG}{dt} = \frac{1}{\theta_2} \left( \frac{ui}{P_0} - 1 \right) \quad (7.7)
\]

where \( i \) is the current, \( P_0 \) is the constant power dissipation by conduction and \( \theta_2 \) is the time constant given by the ratio between the total energy and the part of its losses by conduction.

Lu et al. [76] proposes a physical model that combines (7.6) and (7.7) and considers heat losses by conduction, convection and radiation. This model is adopted here for electrical circuit simulations, since it can provide indications on the DEDM discharge power dissipation by those different mechanisms. This physical model considers the following assumptions:

- The electric discharge plasma energy input is balanced by thermal conduction according to the conductance given by the Mayr equation, whereas losses by convection and radiation are governed by the conductance obtained from the Cassie equation;
- The fraction \( \alpha \) of the electric current \( i \) that passes through the plasma channel corresponds to the energy losses by heat conduction, whereas the remaining fraction...
(1 − α) represents energy losses by convection and radiation. This leads to the equations
\[
\begin{align*}
\iota_{\text{cond}} &= αi \\
\iota_{\text{conv+r}} &= (1 − α)i
\end{align*}
\] (7.8)

- The total conductance of the plasma channel is calculated by summing the conductance given by the different mentioned energy dissipation mechanisms. Thus, the model proposed by Lu et al. [76], which combines (7.6), (7.7) and (7.8), can be described as
\[
\begin{align*}
G_1 &= \frac{αιu}{V_0^2} - θ_1 \frac{dG_1}{dt} + G_0 \\
G_2 &= \frac{(1 − α)^2i^2}{P_0} - θ_2 \frac{dG_2}{dt} + G_0
\end{align*}
\] (7.9)

where \( G_1 \) is the arc conductance given by Cassie equation, \( G_2 \) is the arc conductance given by Mayr equation and \( G_0 \) is the minimum plasma conductance value, which depends on the discharge conditions (electrode gap, electrode geometry, dielectric and temperature). Finally, the model is completed by
\[
\begin{align*}
G_t &= G_1 + G_2 \\
u &= i/G_t
\end{align*}
\] (7.10)

where \( G_t \) is the total plasma conductance. Furthermore, losses by radiation are proportional to the cross-sectional area of the plasma column for a given temperature difference, such as the energy dissipation by convection. Therefore, the discharge radiation power also meets the assumption of the Cassie equation, as demonstrated by Lu et al. [76].

The constant parameters of the used modified Cassie-Mayr model are calculated by the empirical equations and fitting method proposed by Lu et al. [146]. First, three specific voltage values are identified from an analysis of the burning voltage curve of a DEDM discharge, as highlighted in Fig. 7.5. These graph points are the striking peak \( V_1 \), sag point \( V_2 \) and extinguishing peak \( V_3 \). Thus, the value of \( α \) is calculated by
\[
\frac{V_1}{V_2} = 0.36 + 43.8 \cdot e^{-4α}
\] (7.11)

whereas the value of \( θ_1 \) is calculated by
\[
\frac{V_1}{V_2} = 0.9 + 126.3 \cdot θ_1^{1/2}
\] (7.12)

Furthermore, the values of \( V_0 \), \( P_0 \) and \( θ_2 \) are estimated according to the following method:

- \( V_0 \) is estimated by matching the simulated \( V_1 \) with the experimental data;
• $P_0$ is estimated by matching the simulated $V_2$ with the experimental data;
• $\theta_2$ is estimated by matching the simulated $V_3$ with the experimental data.

![Graph showing burning voltage over pulse duration]

Fig. 7.5: RMS burning voltage of a DEDM discharge; Copper point cathode and aluminium plane-type anode; $U_{open} = 250 \, V$; $t = 316 \, \mu s$; Slope-shaped current, $I = 20 \, A$.

DEDM electrical parameters are simulated by the commercial software PSpice [129] with the plasma conductance given by (7.9) and (7.10), as designed in Fig. 7.6. The electrical circuit is modelled with a resistor ($R = 15 \, \Omega$), a capacitor ($C = 20 \, nF$) and a pulsed voltage source $V_p$. The pulsed voltage source drives the electric discharge burning voltage and electric current, simulating the time behaviour of DEDM discharges.

![Electrical circuit model diagram]

Fig. 7.6: Electrical circuit model designed according to Lu et al. [76] and used for PSpice numerical simulations; Copper point cathode and aluminium plane-type anode.
Experimentally measured electric current and discharge voltage are well reproduced by the electrical circuit simulation model, which includes a solver for the modified Cassie-Mayr model. The electrical circuit simulations give a value for $\alpha$ between 0.8 and 0.9, indicating thermal conduction as the dominant energy dissipation effect in the DEDM discharge in comparison with convection and radiation. Simulated and measured DEDM electrical data are presented in the graphs of Fig. 7.7. Furthermore, the constant parameters used in Cassie-Mayr model, obtained according to the procedure described by Lu et al. [76], are presented in Table 3.

![Electric current and discharge voltage graphs](image)

Fig. 7.7: Measured and simulated electric discharge current (a) and voltage (b); Copper point cathode and aluminium plane-type anode; $U_{\text{open}} = 250 \, \text{V}$; $t = 316 \, \mu\text{s}$; Slope-shaped currents, $I = 20 \, \text{A}$.

The graph shown in Fig. 7.8 suggests that the discharge power deposition estimations, calculated by different methods, have very similar values and time behaviours. The results calculated with the Cassie-Mayr model consider the measured discharge power reported in
Fig. 7.4, which is multiplied by the obtained $\alpha$ values and divided by the estimated area of the hot anode spot. These results are in agreement with the simulation results summarized by Kunieda et al. [66] concerning discharges in air as dielectric, who infer that most of the discharge power is dissipated by electrical conduction in the electrode material, whereas losses by convection and radiation can be neglected. Since the discharges investigated here are similar to anode dominated vacuum arcs, as reported in section 5.1.2, one can assume that most of the DEDM discharge energy is deposited onto the anode material.

Table 3: Constant parameters of the used Cassie-Mayr model

<table>
<thead>
<tr>
<th>Cassie-Mayr variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.9</td>
</tr>
<tr>
<td>$V_0$</td>
<td>$14 , V$</td>
</tr>
<tr>
<td>$\theta_1$</td>
<td>$10^{-5} , s$</td>
</tr>
<tr>
<td>$\theta_2$</td>
<td>$5 \cdot 10^{-3} , s$</td>
</tr>
<tr>
<td>$P_0$</td>
<td>$10 , W$</td>
</tr>
<tr>
<td>$G_0$</td>
<td>$2.5 \cdot 10^{-2} , \Omega$</td>
</tr>
</tbody>
</table>

Fig. 7.8: Anode power deposition calculated by different methods; $U_{\text{open}} = 250 \, V$; $t = 316 \, \mu s$; Cu point cathode and Al plane-type anode; Slope-shaped currents, $I = 20 \, A$.

Boxman et al. [12] describes that the energy of a uniform steady-state HAVA deposited onto the anode is mostly converted in thermal conduction into the electrode material $q_c$, radiation of the formed hot spot $q_{re}$ and vaporization of the anode material $q_v$. Therefore, proper modelling of the electrode erosion in DEDM should take into consideration the energy
balance given by those cited dominant dissipation mechanisms, as schematically shown in Fig. 7.9.

Fig. 7.9: Anode energy balance in a HAVA
8. CONCLUSIONS AND OUTLOOK

The present work introduces well-established methods and theories from the field of plasma physics as effective tools for advanced analysis of DEDM discharges and their interactions with the electrode material. Interpretation of OES supported by a commercial CR model allows obtaining much more information on the plasma than the methods conventionally reported in the EDM literature. In addition, the plasma diagnostics used here are supported by physical models and electrical circuit simulations, opening perspectives for deeper analyses of the EDM process under different processing conditions.

Time-resolved OES of DEDM plasmas suggest that discharges performed with point-type cathode are concentrated to a hot anode spot, leading to the formation of a particular type of discharge, the hot anode vacuum arcs (HAVA). Since the cathode is a relatively passive electrode in a HAVA, this property could be the reason for the very small cathode tool wear observed in DEDM, reported in the literature by several researchers. This hypothesis is reinforced by the fact that the cathode tool is coated by anode material during the discharges, which is also a well-known phenomenon of a HAVA. In contrast, both electrodes actively take part in discharges performed with a copper point anode and an aluminium plane-type cathode. Furthermore, considerable erosion levels of the anode tool in DEDM have been reported in the literature by different researchers. This phenomenon probably occurs due the plane cathode geometry, which is not able to concentrate the discharge to a hot anode spot.

Electron temperature values calculated with the two-line Boltzmann method show that the investigated DEDM discharges have cold plasmas. Moreover, the electron density of DEDM plasmas, estimated from the FWHM of the Hα emission line, follows the time behaviour of the electric current. Nevertheless, additional information about the plasma properties, such as populations of high-energy electrons, quantitative estimations of the plasma composition, fraction of ionic species and temperature profiles, cannot be obtained from its optical emission spectrum alone. Investigation of this fundamental information is crucial for a proper understanding of the physics of the DEDM plasma and its interactions with the electrode material, as well as for other EDM processes.

The advanced analysis of OES supported by the used CR model gives a new insight into the complex DEDM discharges, since several important plasma parameters are deduced from emission spectra simulations. An optical depth analysis indicates that the investigated DEDM plasmas are optically thin, so self-absorption of light by the plasma can be neglected. Furthermore, comparisons between numerical and observed optical emission spectra indicate that the analysed DEDM plasmas cannot be fully explained assuming a spatially constant electron temperature. The emission spectra simulations show that the discharges must either have an electron temperature profile peaking at the plasma centre or an electron beam within the discharge, leading to different possible interpretations of the physics of DEDM discharges.
Spatially-resolved OES together with the well-known Abel inversion indicates that DEDM discharges have an electron density profile. This analysis is supported by emission spectra simulations, which give indications on high electron density in the region of the hot spot. Since OES cannot be performed with time and space resolution simultaneously due to limitations of the experimental setup used in the present work, optical fibres with smaller diameter positioned closer to the plasma could be applied in a further investigation to estimate time and spatially-resolved EDM plasma properties.

In order to apply the Abel inversion, the assumption of cylindrical and symmetric DEDM plasmas needs to be made. Possible asymmetries of the discharge plasmas could be treated by tomographic imaging. Tomographic OES could also be used to detect deviations from symmetric plasma behaviour and to investigate their consequences in the plasma-material interactions. Moreover, in addition to the electron density profile estimated in the present work, Abel inversion techniques can reveal spatially-resolved data concerning different parameters within the micro discharge, such as electron temperature, distribution of ionic species and the presence of a non-Maxwellian electron energy distribution. This further investigation could provide profiles of plasma parameters given by several data points, from which plasma properties can be estimated with more precision.

The DEDM discharges investigated in the present work are performed with different electric currents, electrode materials, geometries and polarities. Assuming the formation of an electron beam within the plasma, emission spectra simulations indicate that the electron temperature of discharges performed with copper point cathode and aluminium plane-type anode just slightly varies during the time and does not significantly depend on the applied electric current. Smaller fractions of high-energy electrons of electric discharges performed with current $I = 10 \, A$ suggest the formation of smaller hot anode spots than discharges performed with currents $I = 20$ and $40 \, A$.

Analysis of the DEDM plasma composition reveals that the application of a point cathode leads to the formation of anode dominated discharges independently of the used electric current, electrode material and anode geometry, whereas a plane-type cathode does not concentrate the discharge to a hot anode spot. Analysis of discharges performed under different electric currents with copper point cathode and aluminium point or plane-type anode suggests that the fraction of aluminium content of the plasma drops during the time, while the hydrogen fraction increases. Furthermore, considerably higher fraction of the cathode material is present in the plasma composition of discharges performed with a point aluminium cathode than the ones made with a point-type copper cathode. Plasma composition indications given by emission spectra simulations could be used as inputs in the development of a physical model that estimates the tool electrode wear as a function of its material during the erosion process.

A comparison between discharges in gaseous and liquid dielectric media by advanced plasma diagnostics is also presented. The discharges are performed with copper point and aluminium plane-type electrodes. High-speed imaging measurements indicate that discharges in air as dielectric have a plasma dimension not significantly different from discharges in oil.
for the same adopted working conditions. In addition, such as discharges in gas, emission spectra simulations suggest the presence of a temperature profile in discharges performed in liquid dielectric for both electrode polarities. Assuming regions of the plasma with distinct properties, the simulations indicate the existence of a hotter region at the centre of the plasma, compatible with the formation of a hot spot, and a colder region, which corresponds to the plasma plume. The calculated electron temperatures are very similar for all applied processing conditions, around 15,000 $K$ ($\sim 1.29 \text{ eV}$) in the plasma plume, and about 21,000 $K$ ($\sim 1.81 \text{ eV}$) in the hot spot region of the plasma. Electron densities of discharges performed in oil are up to 8 times higher in the beginning of the discharge than the ones calculated for discharges in air as dielectric. Moreover, a coupling between the temporal behaviour of the gas bubble formed around the discharge in oil and the electron density of the plasma is observed.

Electric discharges in air are dominated by metallic species from the electrode material, whereas discharges in oil are mainly dominated by hydrogen and carbon originated from the dielectric with some metallic contamination from the electrodes. Furthermore, the metallic content of discharges in oil slightly decreases during the time. In a further investigation, spatially-resolved absolute density of species could be quantified by optical absorption spectroscopy (OAS) of EDM plasmas. The observed optical absorption spectra of the plasma can be properly interpreted applying the Abel inversion with support of a CR model. The analysis of post-discharges by OAS can reveal properties of the medium in the gap and conditions for a following next electrical breakdown. In addition, even beyond EDM, knowledge concerning the post-discharge characteristics is crucial for the development of many other industrial applications, such as design of electrical devices with micrometre separations and definition of their electrical parameters.

Anode power deposition in DEDM, resulting from plasma-material interactions, is also estimated in the present work by different methods. Electrical circuit simulations using a modified Cassie-Mayr model suggest that the discharge power losses are governed by heat conduction. According to indications given by electrical circuit simulations, 80% to 90% of the discharge power flows into the anode material, whereas the remaining plasma energy is dissipated by convection and radiation. The energy absorbed by the cathode material can be neglected for the applied experimental conditions, since anode dominated discharges are formed. Furthermore, the electrical circuit simulations outcomes are supported by calculations of the anode heat flux by a thermal plasma. These calculations consider particular properties of the involved discharges, discovered by OES interpretation. Magnetohydrodynamics models could be developed in the future in order to simulate and predict profiles of EDM plasma properties and their effects on the electrode power deposition. It is also important to state that the fraction of discharge power deposition presented in this work is substantially larger than the ones reported in the EDM literature, which are based on heat transfer simulations. Energy transferred to the anode in a HAVA is substantially dissipated by radiation of the hot spot and vaporization of the anode material. Therefore, the application of heat transfer models might be an oversimplified solution for the discharge
power deposition estimations. In future investigations, more sophisticated crater models, which should include those mentioned physical phenomena, could be developed considering the inputs given by the advanced plasma diagnostics reported in the present work.


[47] https://www.phantomhighspeed.com/Products/Phantom-High-Speed-Cameras-Super-Slow-Motion-Cameras/v121.


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