Numerical analysis and simulation of micro- EDM plasma in de-ionised water

Leeba Varghese¹, P Vysakh and K K Manesh
Department of Mechanical Engineering, Government Engineering College Thrissur, Kerala, India
¹Email: leebavarghese1982@gmail.com

Abstract. Micro-EDM is extensively used for the manufacture of miniature components in the field of biomedical, aerospace and automobile applications, where the surface integrity of the manufactured component is a crucial factor. But it has still not replaced other manufacturing methods like Laser Beam Machining because of its low energy efficiency. In order to improve the process efficiency and make it a commercially viable, so many parametric studies have been conducted, considering the various input and output parameters involved. Very little effort is taken in the direction of studying about the plasma, which is the actual source of energy in micro- EDM. This is due to difficulty in analysing it as the plasma lasts only for a few micro seconds in micro- EDM. The existing studies about plasma formation and its role in material removal in a micro EDM process is lacking in many respects, considering the underlying mechanism of plasma formation. This simulation is an attempt to bridge that gap. A one-dimensional model, based on fluid dynamic approach, considering the chemistry involved in plasma formation is simulated. The evolution of plasma characteristics was studied for one level of electric field and gap width. The results obtained for electron density is compared with experimentally obtained results and is found to be in close agreement. The value of temperature obtained is much lower compared to that found in literature. This shows that the data imported as chemical reactions is not complete in all respects. The simulation requires further improvement.

1. Introduction
Micro Electric Discharge Machining (Micro EDM) is an advanced manufacturing process, which makes use of thermal energy of the spark produced between two electrodes immersed in a dielectric medium for material removal. An electric potential is applied between the tool and work piece electrodes by using a Resistance-Capacitance (RC) circuit. When breakdown potential of the dielectric is reached, it tends to break down into ions by releasing electrons. This breakdown process is initiated by primary electrons emitted by cathode, the tool electrode. Breakdown of the dielectric releases secondary electrons, through a series of ionization reactions and results in a plasma channel being formed. The resulting avalanche of electrons is seen as the spark which will last only for a few micro seconds. The bombardment of these ions and electrons on the surface of the tool and work piece respectively, causes melting of corresponding electrodes and thereby material is removed from their surface.

Micro EDM is capable of material removal at sub grain size range and this is used for producing miniature components used in various fields like aerospace, automobile and biomedical applications. The main drawback of Micro EDM is low process efficiency due to low energy utilization. In order to improve this efficiency, it is necessary to study the underlying process mechanism. The plasma
channel formed lasts only for a few microseconds and therefore, it is very difficult to monitor its characteristics under different input conditions. So, material removal mechanism can be better understood if plasma generation is modelled, considering the physics behind the process.

2. Literature Review and the Gaps Identified

Dibitonto et al. [1] developed a cathode erosion model considering plasma as a point heat source. The heat conducted by the plasma is governed using one dimensional heat conduction equation and the radius of the melt pool is calculated at small increments of pulse time [2]. Dibitonto et al. also developed an anode erosion model in which plasma was considered as a Gaussian distributed heat source. Heat transfer to the anode was considered to be unsteady heat conduction. The fraction of power going to the anode was determined to be around 8-9%. They calculated the erosion rate at the anode considering that the molten metal resolidifies at the anode [3].

Eubank et al. developed a variable mass cylindrical plasma model. Equations of continuity and momentum were applied to the surrounding dielectric liquid against which plasma expanded. Mode of heat transfer to the liquid was assumed to be due to radiation due to the short time period involved. Seven reactions in the plasma involving ten species were considered and their dissociation and ionisation energies were also included [4]. Dhanikand Joshy prepared a comprehensive model of the micro-EDM plasma incorporating various phenomena in the pre-breakdown period. Navier stokes equations were applied for the expansion of plasma, considering mass addition to the plasma and its viscosity [5].

Xuyang et al. further analysed the forces resisting the expansion of plasma, the viscous force, magnetic pinch force and surface tension force. The energy produced at the plasma is transferred to the dielectric through radiation for vaporization and decomposition of the dielectric [6].

In all these models, the energy produced by each pulse is calculated using the relation:

\[ E = \int_{0}^{t} UIdt \]  

Where, \( E \) is the discharge energy, \( t \) represents pulse duration, \( U \) denotes discharge voltage and \( I \) refer to discharge current. Heat lost to the work piece is governed by the three-dimensional heat conduction equation [1].

It can be seen that most of the plasma models available in the literature considers plasma as a predefined type of heat source and calculates the amount of material removed at anode and cathode considering that out of the total energy produces by the pulse, around 26% (empirically determined) goes to the electrodes and the remaining 74% is used for the expansion of plasma against the resisting forces exerted by the dielectric. In all these models, plasma has been considered as a fluid, and the laws of conservation used in fluid dynamics were applied. In fact, plasma is a collection of electrically charged particles and neutral particles which interact with each other, with the internally generated fields as well as with the externally applied fields. So, in order to analyze a plasma, an approach has to be formulated considering these as well as the chemistry of plasma formation, considering the various types of reactions involved-ionization, excitation and dissociation reactions. These reactions have a significant influence on the evolution of plasma temperature, pressure and radius.

Mujumdar et al., developed a global plasma model, a kinetic approach, by simultaneously solving the particle balance and power balance equations and predicted the plasma characteristics that influence the material removal process namely, the size of the plasma (radius), heat flux transferred to the electrodes, and the pressure force exerted on the electrode surfaces [7]. This approach considers the reaction kinetics in the dielectric fluid as well as the bubble dynamics. They have also developed a melt pool model of the micro EDM discharge based on plasma radius, heat flux and pressure inputs from the micro EDM plasma model [8].

In this work, plasma is considered as a fluid consisting of interacting charged particles. A statistical approach using kinetic theory is applied to calculate the physical features like temperature and pressure by using a set of governing equations, which are deduced from the Boltzmann equation.
3. Simulation of plasma

3.1. Plasma chemistry

The domain under consideration is the region between the two electrodes, which is filled with dielectric. An external electric field is applied between the two electrodes by means of an external R-C circuit. Initially, some free electrons are assumed to be present in the dielectric. These free electrons start moving due to the applied voltage, initializing chemical reactions in the dielectric, resulting in further release of electrons. At this point, the dielectric breaks down and electrons start moving towards the anode and ions start moving towards the cathode in large numbers. This secondary emission of electrons results in the formation of an avalanche of electrons and ions between the work piece and tool, which appears as the spark in the plasma channel [9,10].

These reactions, results in the ionisation of the plasma channel and release of a large amount of energy, which eventually contributes to material removal. The chemistry of this particular plasma is formulated from the database of Itikawa [16] which is provided in the LXCAT database [11]. This model consists of 5 attachment reactions, 9 elastic reactions, 37 excitation reactions and 10 ionization reactions identified from the database. These reactions are listed in Table 1. Collision cross section (σ), the area available for electron collision to take place, is the parameter that determines the probability of a collision which in turn cause several reactions such as elastic, excitation, ionisation and recombination to occur. Cross-sectional data corresponding to different energy levels are also obtained for each reaction from LXCAT database. The rate constant for all reactions is calculated based on this cross-sectional data and is used to solve the governing equations of plasma [17]. The simulation procedure is shown in Figure 1.

![Figure 1. Simulation procedure (a) using BOLSIG+ (b) using COMSOL](image-url)
Table 1. Reactions in the dielectric

| Sl. No. | Reaction               | Sl. No. | Reaction               |
|--------|------------------------|--------|------------------------|
| 1      | Attachment             | 32     | E+H2 => E+H+H          |
| 2      | attachment             | 33     | E+H2 => E+H2           |
| 3      | Elastic                | 34     | E+H2 => E+H2           |
| 4      | Elastic                | 35     | E+H2 => E+H2           |
| 5      | Elastic                | 36     | E+H2 => E+H2           |
| 6      | Elastic                | 37     | E+H2 => E+H2           |
| 7      | Elastic                | 38     | E+H2 => E+H2           |
| 8      | Elastic                | 39     | E+H2 => E+H2           |
| 9      | Elastic                | 40     | E+O2 => E+O2           |
| 10     | Elastic                | 41     | E+O2 => E+O2           |
| 11     | Elastic                | 42     | E+O2 => E+O2           |
| 12     | Elastic                | 43     | E+O2 => E+O2           |
| 13     | Elastic                | 44     | E+O2 => E+O2           |
| 14     | Elastic                | 45     | E+O2 => E+O2           |
| 15     | Excitation             | 46     | E+O2 => E+O2           |
| 16     | Excitation             | 47     | E+O2 => E+O2           |
| 17     | Excitation             | 48     | E+O2 => E+O2           |
| 18     | Excitation             | 49     | E+O2 => E+O2           |
| 19     | Excitation             | 50     | E+O2 => E+O2           |
| 20     | Excitation             | 51     | E+O2 => E+O2           |
| 21     | Ionisation             | 52     | E+H2O => E+H+H2O+      |
| 22     | Ionisation             | 53     | E+H2O => E+H+H2O+      |
| 23     | Ionisation             | 54     | E+H2O => E+H+H2O+      |
| 24     | Ionisation             | 55     | E+H2O => E+H+H2O+      |
| 25     | Ionisation             | 56     | E+H2O => E+H+H2O+      |
| 26     | Ionisation             | 57     | E+H2O => E+H+H2O+      |
| 27     | Ionisation             | 58     | E+H2O => E+H+H2O+      |
| 28     | Ionisation             | 59     | E+H2O => E+H+H2O+      |
| 29     | Ionisation             | 60     | E+H2O => E+H+H2O+      |
| 30     | Ionisation             | 61     | E+H2O => E+H+H2O+      |
| 31     | Ionisation             | 62     | E+H2O => E+H+H2O+      |

3.2. Computational Domain

A one-dimensional model of µ-EDM system is taken as shown in Figure 2. Anode and cathode are separated by a dielectric of deionized water in 1 µm distance. Copper is assigned to the anode and Nitinol is assigned to the cathode. Deionized water, used as dielectric is made to flow in the domain 2-3. Boundary 4 is grounded. Boundary 1 is applied with a terminal voltage, provided by the external R-C circuit.

Plasma is formed in the domain 2-3. In this research, a fluid model approach is followed, where, plasma is considered as a fluid containing charged particles. A small volume called phase space is defined with in this domain. The number of particles inside the phase space at any instant of time is
defined as Electron Energy Distribution Function. The value of EEDF is obtained by solving the Boltzmann Equation [12].

3.3 Governing Equations
For a given set of chemical reactions, the electron energy distribution function (EEDF) is calculated by solving the Boltzmann equation (BE) by the BOLSIG+ solver using two term approximation technique. The BE for electrons in an ionised gas is given by

\[
\frac{\partial f}{\partial t} + v \cdot \nabla f - \frac{e}{m} E \cdot \nabla_v f = C[f]
\]

(2)

Where, \(f\) is the EEDF, \(v\) are the velocity coordinates, \(e\) is the elementary charge, \(m\) is the electron mass, \(\nabla_v\) is the velocity gradient operator and \(C\) represents the rate of change in \(f\) due to collisions [15].

Rate coefficients and transport coefficients required for the fluid models are obtained from the solution of the electron Boltzmann equation.

Rate coefficients are calculated from the cross-sectional data and EEDF

\[
k_k = \gamma \int_0^\infty \sigma_k(\epsilon) f(\epsilon) \, d\epsilon,
\]

where, \(\gamma=(2q/me)^{1/2}\), \(\sigma_k\) is the collision cross section and \(f\) is the electron energy distribution function.

For analysis of the transport properties, a bunch of electrons is considered which drifts through the dielectric under the action of an externally applied electric field \(E\). Two transport properties are considered.

1. Mobility: The externally applied electric field causes the electrons to gain energies much higher than their mean energy. So, the electron drift velocity is determined from energy distribution function and cross sections.

2. Diffusion: In electric discharge, when there is a non-uniform concentration of charges, there will be migration of these charges from region of higher concentration to region of lower concentration. This process is called diffusion.

For computing the electron density and electron energy, these coefficients are transferred to the fluid equations. Thus, maximum consistency is ensured between the kinetic and fluid description of electron dynamics.

The fluid model solved in the COMSOL Multiphysics software uses the moments of the BE to get the following equations [13,14]:

The continuity equation

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot n_e u = R_e
\]

(4)

Where \(n_e\) is electron density, \(R_e\) is the source term.

The momentum equation (approximated by the drift diffusion equation)

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot [-n_e(\mu_e E) - D_e \nabla n_e] = S_{\alpha}
\]

(5)

Where \(\mu_e\) is the electron mobility and \(D_e\) is the electron diffusivity. Convection of electrons due to fluid motion is neglected.

The energy equation

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot [-n_e(\mu_e E) - D_e \nabla n_e] + E \cdot T_e = R_e
\]

(6)

Where \(n_e\) is the energy density, \(\mu_e\) is the energy mobility, \(D_e\) is the energy diffusivity, and \(T_e\) is the electron flux.

These values are calculated from electron mobility using
\[ D_e = \mu_e T_e, \mu_e = \left( \frac{5}{3} \right) \mu \epsilon, D_\epsilon = \mu_\epsilon T_\epsilon \] \hspace{1cm} (7)

### Table 2. Initial values for simulation

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Temperature                | 373.15 K               |
| Pressure                   | 1 atm                  |
| Applied voltage            | 40 V                   |
| Electron mobility (\(\mu\)) | 0.5841e24 (1/m.V.s)    |
| Electron density           | 1.286e18 (1/m^3)       |
| Mean electron energy       | 5 V                    |
| Mixture density            | 997 kg/m^3             |

### 3.4 Boundary Conditions

The boundary conditions are specified by giving a set of surface reactions, which sustains the plasma through generation or loss of ions and electrons. The secondary emission flux is calculated by the software from the surface reactions given.

At the wall, the exchange of electrons occurs through the following mechanisms:

- Electrons lost due to a net flux of electrons from the plasma bulk to the surface of the work piece
- Electrons lost due to the random motion of electrons within the mean free path of the wall
- Electrons gained due to secondary emission from the wall, when it is hit by a positive ion
- Electrons gained due to thermionic emission
- Migration effects of electrons due to the static electric field

These factors are taken care of by the following equations.

\[ n \cdot \Gamma_e = \frac{1-r_e}{1+r_e} \left( \frac{1}{2} v_e, n_e + n_e (\mu_e, E) \cdot n \right) - \left[ \Sigma \gamma_i (\Gamma_i \cdot n) + \Gamma_i \cdot n \right] \] \hspace{1cm} (8)

\[ n \cdot \Gamma_\epsilon = \frac{1-r_\epsilon}{1+r_\epsilon} \left( \frac{5}{6} v_\epsilon, n_\epsilon + n_\epsilon (\mu_\epsilon, E) \cdot n \right) - \left[ \Sigma \epsilon_i \gamma_i (\Gamma_i \cdot n) + \epsilon_i \Gamma_i \cdot n \right] \] \hspace{1cm} (9)

### 4. Results and Discussion

The present model of micro EDM plasma helps to understand the evolution of plasma by observing various plasma characteristics namely electron temperature, electron density and electric potential. Collisional cross section data associated with each reaction corresponding to different energy levels (Figure 3) is taken from LXCAT database. This data is fed to BOLSIG+ solver. The solution of Boltzmann equation is Electron Energy Distribution Function (Figure 4), obtained using 2 term approximation technique. EEDF gives an idea about the overall nature of discharges. The EEDF obtained are further used to calculate the rate coefficients, shown in Figure 5 which serves as inputs to the drift diffusion equations.

**Figure 3.** Cross sectional data for each reaction

**Figure 4.** EEDF at different energy levels
Mobility and diffusion are the two transport properties considered in this analysis. The values of these transport coefficients are calculated by the BOLSIG plus solver and given as input to the fluid equations. Table 3 shows the values of reduced electron transport properties, converged after 30 iterations of the BOLSIG plus solver.

4.1 Effect on electron density

In the simulation experiment, an inter electrode gap width of 1μm is provided with the initial value of voltage. Electric field (E) applied and current density (J) are calculated by the software. The simulation is done for one level of electric field and one level of gap width.

Figure 6 represents the variation of electron density along the inter electrode gap. The density near the walls tends to reduce since the electrons and ions tend to recombine there. Initially, one or more peaks are expected between the walls where there is maximum collision. As time progresses, the ions and electrons will tend to diffuse towards regions of low density and the overall density becomes uniform along the inter electrode gap.
4.2 Effect on electron temperature

Figure 7 displays electron temperature at the end of simulation. If the plasma volume is considerably high, it facilitates provision for more inter particle collisions, which in turn will increase the electron temperature. Thus, it is expected that the temperature shows an increasing trend towards the centre of the inter electrode gap. But in this simulation, temperature shows a decreasing trend. This could be because, at the end of discharge, plasma extinguishes and recombination of the dielectric takes place. Out of the three stages in plasma generation, the ignition phase, heating phase and removal phase; the removal phase is characterised by regeneration of the spark gap. Also, the number of reactions considered here does not completely represent the total reactions taking place in the dielectric.

![Figure 7](image)

**Figure 7.** Effect of applied electric field on electron temperature with respect to gap distance

**Table 3.** Swarm parameters obtained from BOLSIG+

| Electron Transport Properties               |
|---------------------------------------------|
| Reduced Electron Mobility \((\mu_eN_n)\)      |
| Reduced Electron Diffusivity \((D_eN_n)\)    |
| Reduced Electron Energy Diffusivity \((D_{ee}N_n)\) |
| Reduced Electron Energy Mobility \((\mu_{en}N_n)\) |

| Reduced Electron Mobility \((\mu_eN_n)\) | 0.5841E24 (1/V.m.s) |
| Reduced Electron Diffusivity \((D_eN_n)\) | 0.3895E24 (1/m.s)  |
| Reduced Electron Energy Diffusivity \((D_{ee}N_n)\) | 0.5093E24 (1/m.s) |
| Reduced Electron Energy Mobility \((\mu_{en}N_n)\) | 0.7639E24 (1/V.m.s) |

**Table 4.** Comparison of experimental and simulation results

| Process parameters | Experimental [19] | Simulation |
|--------------------|-------------------|------------|
| Voltage [V]        | 40, 45, 50        | 40         |
| Inter electrode gap [µm] | 0.5, 1, 2   | 1          |

| Results |
|---------|
| Electron density \([m^3]\) | 23.9x10^{23} | 1.26x10^{18} |
| Temperature [K] | 6217 | 372 |
5. Conclusion
A numerical analysis of plasma was conducted and simulated using COMSOL Multiphysics software. Transport equations, obtained by taking moments of Boltzmann equation, serves as the governing equations. The macroscopic variables, electron temperature and electron density are calculated from this fluid dynamic model. The collision term incorporates the effects of ionization, recombination and electron attachment. The following conclusions are derived from the investigation.

1. The model is validated using the experimental results obtained from the spectroscopic measurement [18] of single discharges conducted by Nagahanumaiah et al [19]. The electron density obtained in the referred experiment is $23.9 \times 10^{23}$ m$^{-3}$, which is comparable to $1.26 \times 10^{18}$ m$^{-3}$ given by the simulation.

2. The temperature obtained here is much lower than that obtained in the spectroscopic measurement. This could be because the figure shows the final stage of the process when the plasma extinguishes and the dielectric starts to recombine. Another reason could be because the plasma chemistry considered does not incorporate all the chemical reactions involved in the formation of plasma. Therefore, the simulation requires further improvement, in terms of the chemical reactions involved.

3. For more accurate results, the physics of hydrodynamics of bubble formation, should also be added.

References
[1] Tlili A, Ghanem F and Salah NB 2015 A contribution in EDM simulation field Int. J. Adv. Manuf. Technol. 79 921-35
[2] DiBitonto DD, Eubank PT, Patel MR, and Barrufet MA 1989 Theoretical models of the electrical discharge machining process I. A simple cathode erosion model J. appl. Phys. 66 4095-103
[3] Patel MR, Barrufet MA, Eubank PT and DiBitonto DD 1989 Theoretical models of the electrical discharge machining process II. The anode erosion model J. appl. Phys. 66 4104-11
[4] Eubank PT, Patel MR, Barrufet MA and Bozkurt B 1993 Theoretical models of the electrical discharge machining process. III. The variable mass, cylindrical plasma model J. appl. Phys. 73 7900-09
[5] Dhanik S and Joshi SS, 2005 Modelling of a single resistance capacitance pulse discharge in micro-electro discharge machining J. Manuf. Sci. Eng 127 759
[6] Chu X, Zhu K, Wang C, Hu Z and Zhang Y 2016 A study on plasma channel expansion in micro-EDM Mater. Manuf. Process 31 381-90
[7] Mujumdar SS, Curreli D, Kapoor SG and Ruzic D 2014 A model of micro-electro-discharge machining plasma discharge in deionized water J. Manuf. Sci. Eng. 136 031011-1
[8] Mujumdar SS, Curreli D, Kapoor SG and Ruzic D 2015 Modeling of melt-pool formation and material removal in micro-electrodischarge machining J. Manuf. Sci. Eng. 137 031007
[9] Jones HM and Kunhardt EE 1995 Development of pulsed dielectric breakdown in liquids J. Phy. D: Appl. Phy. 28 178-88
[10] Dhanik S, Joshi SS, Ramakrishnan N and Apte PR, 2005 Evolution of EDM process modelling and development towards modelling of the micro-EDM process Int. j. manuf. Tech. manag. 7 157-180.
[11] www.lxcat.net
[12] Lieberman M A and Litchenberg A J 2005 Principles of Plasma Discharge and Material Processing (New York: Wiley) pp 327-80
[13] Bittencourt J.A. 2004 Fundamentals of Plasma Physics (New York: Springer) pp 122-36
[14] Chen F 1974 Introduction to Plasma Physics and Controlled Fusion (New York:Plenum Press)pp 53-77
[15] HageaarGJM and PitchfordLC2005 Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models Plasma Sources Sci. and
[16] Itikawa Y and Mason N, 2005 Cross sections for electron collisions with water molecules. J. Phy. Chem. ref. data 34 1-22

[17] Liu DX, Bruggeman P, Iza F, Rong MZ and Kong MG 2010 Global model of low-temperature atmospheric-pressure He+ H2O plasmas Plasma Sources Sci. Tech. 19 025018-22

[18] Descoeudres A, Hollenstein C, Wälder G, Demellayer R and Perez R 2008 Time-and spatially-resolved characterization of electrical discharge machining plasma Plasma Sources Sci. Tech. 17 024008-18

[19] Ramkumar J, Glumac N, Kapoor S G and DeVor RE, 2009 Characterization of plasma in micro-EDM discharge using optical spectroscopy J. Manuf. Proces. 11 82-87