# NUMERICAL MODEL AND SIMULATION OF STREAMING ELECTRIFICATION IN A MODIFIED COUETTE SYSTEM

Daria Wotzka
Department of Electrical Engineering Automatic Control and Informatics
Opole University of Technology
45-759, Opole, Poland
E-mail: d.wotzka@po.opole.pl

**KEYWORDS**
Streaming electrification, numerical model, FEM, computer simulation, modified Couette system.

**ABSTRACT**

The paper deals with multiphysical modeling of streaming electrification phenomena occurring in a modified Couette system filled with electro insulation oil. The electrification process occurs during flow of liquids of low conductivity, e.g. in certain chemicals, fuels or mineral oils. In this paper a numerical model of the streaming electrification process is presented. Computer simulations have been conducted in order to determine the behaviour of the electrification current under various conditions. The differences between the impact of amplitude and diffusion level on the charge concentration within the analyzed domain were investigated. The model design and selected results depicting the impact of various model parameters are included in this paper.

## INTRODUCTION

The goal of the research task whose results are presented in this paper was to determine a numerical model of the streaming electrification process occurring in a modified Couette system and to perform a theoretical investigation of the influence of various parameters on the achieved results.

The streaming electrification phenomenon relates to charge accumulation at specified locations in liquids of low conductivity (e.g. certain chemicals, fuels or mineral oils) especially at higher velocities and with increased field intensities flowing through pipes(Egan 2017; Hu et al. 2017; Liu et al. 2017; Talhi et al. 2016; Zhou et al. 2016). This process is due to generation, conduction, diffusion and convection of electric charge. If the accumulated discharge exceeds the threshold value, electrical discharges may occur, which in turn may lead to dangerous situations and even critical accidents. This phenomenon is an issue in equipment using dielectric liquid, which relates to, for example, high power transformers, oil tanks and gas stations (Chen et al. 2015; Du et al. 2017; Wei et al. 2016). Theoretical and practical investigations into the phenomenon of streaming electrification may allow engineers to design secure and reliable systems, in which flow of low-conductivity liquids may lead to electrification processes. Further, it may be crucial in the energy, chemical and petrochemical sectors.

There exist a great number of works considering theoretical and practical aspects of streaming electrification phenomena occurring in dielectric liquids, performed by Touchard et al., e.g. (Touchard 1978, 2001; Touchard et al. 1996), Gibbings, et al., e.g. (Gibbings 1970, 1987), Cabaleiro et al.(Cabaleiro et al. 2016), Clermont et al.(Clermont et al. 2017), Leblanc et al. (Leblanc and Paillat 2016) and Paillat et al. (T Paillat et al. 2012; Paillat et al. 2001). Electrification in Couette flow was investigated by Zahn et al., e.g. (Jansen and Zahn 1991; Lyon et al. 1988; Morin et al. 1991; Washabaugh and Zahn 1996). Works considering measurements and analytical issues of streaming electrification occurring in a rotating system were investigated in, e.g. (Zmarzly and Fracz 2016; Zmarzly 2009a; 2009b; Zmarzly et al. 2015). Significant works on numerical simulations of streaming electrification were performed by El-Adawy et al. in (El-Adawy et al. 2010a; 2010b, 2011).

The main purpose of the work whose results are presented in this paper was to find a computer model that properly describes the streaming electrification process. There are a lot of parameters that can influence the results (Du and Zhang 2016; Nouri et al. 2016; Ruochen and Hongfu 2017). The main issue in this case is the necessity to adopt a large number of assumptions and approximations, e.g. turbulence modeling simplification (Huang et al. 2016). However, on the basis of preliminary works and research conducted in the flow system (Zmarzly and Fracz 2016) and based on numerical studies conducted by other contractors and that presented in this paper, it was confirmed that it is possible to achieve numerically satisfactory results. Based on analysis of the calculations presented here and those previously achieved, it may be stated that the simulation results are in line with measurement data presented in the literature.

The main contribution of this paper lies in the design and implementation of the numerical model and the determination of the time and space distributions of concentration, velocity and current density in the considered geometry under laminar conditions using COMSOL Multiphysics commercial software. Further, results of numerical simulations of streaming electrification current during Morlet-type oscillations are presented.

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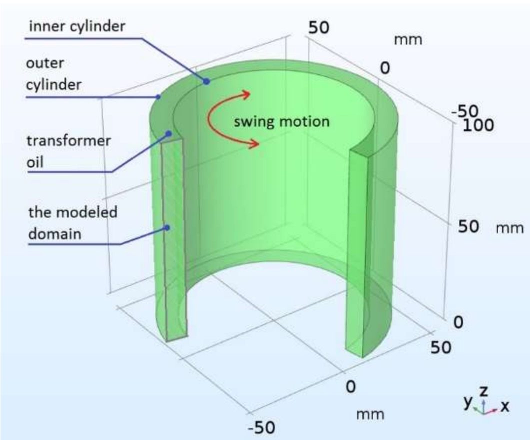
## MATERIALS AND METHODS

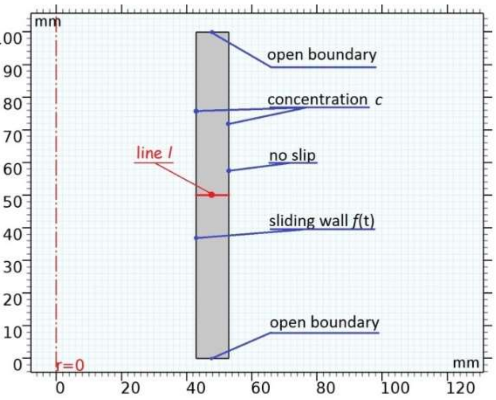
One of the basic types of systems for streaming electrification measurements is the rotating system. This system uses a spinning disk or a rotating cylinder and enables the measurement of electrification current or voltage, based upon which the charge is then calculated. In the research, the author designed a computer model of a swinging system, which is a modification of the Couette system and was proposed in (Zmarzły 2012). The Couette system uses coaxial cylinders. The inner cylinder is able to rotate in both directions with a specified speed. The system therefore allows for continuous measurement of electrification.

The subtasks were as follows: preparation of the simulation environment; definition of appropriate assumptions and minimal simplifications which maintain computational validity; geometry design; meshing; implementation of governing equations and preparation of solver; definition of boundary conditions; execution of simulations within the model; analysis of results; comparison of results against the experimental results of studies presented in, e.g. (Metwally 1996; Zmarzly and Fracz 2016; Zmarzly 2013; Zmarzly et al. 2015, 2017). The model geometry was built assuming geometry and parameters corresponding to experimental measurements given by (Zmarzły 2012). In order to perform calculations within a reasonable time on infrastructure available to the author, the model was simplified to a cylinder as depicted in Figure 1.




Figures 1: Section of the Couette facility implemented in the simulation program depicting the modelled domain

The outer cylinder is fixed, while the inner cylinder swings according to a defined movement. Since the object under study is symmetrical, only a 2D section was considered in calculations (see Figure 2). The space between the cylinders is filled with transformer oil, which for the defined temperature $T$=293 K has the following parameters: dynamic viscosity: 0.02 Pa*s; heat capacity: 1720 J/(kg*K); density: 879 kg/m$^3$; thermal conductivity: 0.1107 W/(m*K). In the available literature, the values of diffusion coefficient $D$ vary in the range of approximately $10^{-9}$–$10^{-12}$ (Bauer 2012; El-Adawy et al. 2011; Leblanc et al. 2016; Palmer and Nelson 1997) but previous numerical studies led to the conclusion that the value may be much higher for transformer oils. Therefore, $D$ was varied from $10^{-6}$ to $10^{-12}$ in the present study. The considered domain was divided into finite elements. The mesh size was investigated maintaining the optimal element quality. The resulting mesh consists of 31,522 triangular elements, 786 edge elements and 16,155 mesh vertices, and the resulting number of DoF equals 65,410. The minimum element quality is 0.6719, while the average element quality is 0.97. The mentioned metrics were calculated using skewness.




Figures 2: The boundary conditions applied in numerical simulations

The governing equations applied in calculations are given by Equations (1–7). Fick's law describes diffusive transport in a flux and is adequate when the diffusing species is dilute with respect to a solvent. It was assumed that the transport of species is due to diffusion and convection. The mass balance equation is as follows from Equations (1) and (2). The flux **N** [mol/(m$^2$s)] is calculated according to Equation (2).

$$\frac{\partial c}{\partial t} + \nabla \cdot (-D\nabla c) + \mathbf{u} \cdot \nabla c = 0 \qquad (1)$$

$$\mathbf{N} = -D\nabla c + \mathbf{u}c \qquad (2)$$

where: $c$ [mol/m$^3$] is the concentration of species, $D$ [m$^2$/s] is the diffusion coefficient, **u** [m/s] is the velocity vector, which is calculated from Equation (3). The Navier–Stokes equation, which relates to the oscillating cylinder (sliding wall depicted in Figure 2) is presented in Equation (3).

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left(-\rho\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^{\mathrm{T}})\right) \qquad (3)$$
$$\rho\nabla \cdot (\mathbf{u}) = \mathbf{0}$$

In the present work we omitted the term for migration: $-q\gamma/\varepsilon$, since we assume analysis of dielectric liquid flowing through in a macroscopic model as compared to the Debye length, which is in the order of nanometers. It was therefore assumed that charge displacements due to migration phenomena, which occur at the boundary of the cylinder wall (metal) and transformer oil (insulator), may be neglected. Further, we consider that no external electrical field is applied, nor are there any electrodes within the model, which could produce migration of ions within the object at a macroscopic scale. Based on (Miyamoto and Miura 1989) and (Metwally 1996) it was further assumed that the streaming current $i$ is proportional, including a constant multiplicity α to the carrier (particles) concentration $c$ and in the case of laminar flow, to the flow rate $U$, thus: $i=\alpha c U$. Since there is no external electrical force acting on the system, the relationship between $i$ and conductivity was omitted. The accumulation of particles is represented by the first term of Equation (1). The convection assumes an incompressible flow without turbulences (laminar flow was applied). The inner and outer cylinders are overcharged with a concentration equal to 1e-9 mol/m$^3$. The specified boundary conditions are depicted in Figure 2. The initial values for calculations are as follows: $u$=[0,0] m/s, $p$=0 Pa, $c$=0 mol/m$^3$. The open boundary for transport of charges, assuming normal stress equal to 0 N/m$^2$ is given by Equation (4).

$$\left(-\rho\mathbf{I}+\mu(\nabla\mathbf{u}+(\nabla\mathbf{u})^{\mathrm{T}})\right)\mathbf{n}=0 \qquad (4)$$

The open boundary for convection and diffusion is given by Equations (5) and (6).

$$c=c_0,\ \ dla\ \ \mathbf{n}\cdot\mathbf{u}<0 \qquad (5)$$

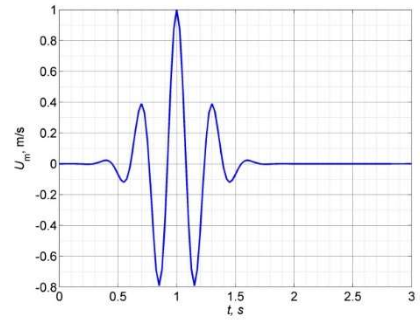
$$-\mathbf{n}\cdot D\nabla c=0\,,\ \ dla\ \ \mathbf{n}\cdot\mathbf{u}\geq 0 \qquad (6)$$

The open boundary was used to transport mass across boundaries. It specifies exterior species concentration on parts of the boundary where fluid flows into the domain. The third term accounts for the convective transport due to a velocity field **u**. This field was obtained from coupling to fluid flow due to momentum balance. The movement of the inner cylinder $U_m$ was defined by a Morlet-type function (7), visualized in Figure 3.

$$F_{Morlet}(t)=\mathrm{A}e^{-\left(\frac{t-\mathrm{B}}{\mathrm{C}}\right)^2}\cos\left(f(t-\mathrm{B})\right) \qquad (7)$$

where: A, B, C – const. parameters; $t$ – time; $f$ – frequency.

The no-slip condition is defined as **u**=0. Sliding wall conditions are defined as **u**=$F_{Morlet}(t)$. The value of parameter $A$ in Equation (7) was varied in the range of 0.06 to 5 m/s, which corresponds to a Reynolds number up to 4,256. This was due to the assumption of a laminar flow regime and was also determined by fitting to the experimental setup.

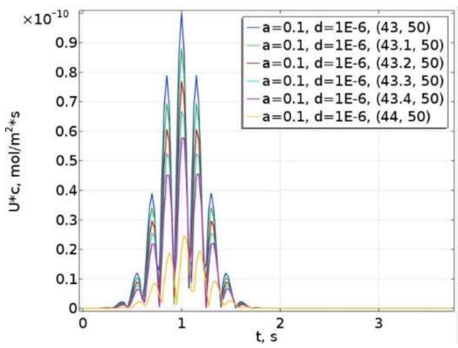



Figures 3: Example waveform of the cylinder oscillations $F_{Morlet}$ by $A$=1, $B$=1, $C$=0.1, $f$=20

## RESULTS AND DISCUSSION

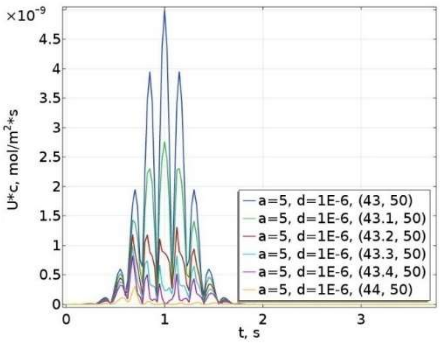
During the research works the impact of the following parameters of the simulation model were investigated: diffusion coefficient $D$, frequency $f$, amplitude $A$. The space and time distribution of concentration and velocity and the multiplication of both from the considered parameters were investigated.

Figures 4 and 5 present the waveforms of charge distribution, which was calculated as the product of velocity magnitude and concentration $U*c$ at various points in the vicinity of the oscillating wall for diffusion $D$=1e-6 for the Morlet-type inclination of amplitude $A$=0.1 m/s and $A$=5 m/s, respectively.

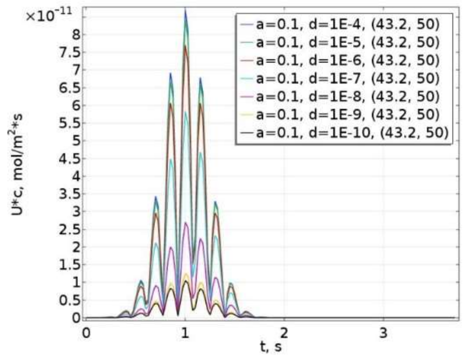



Figures 4: Development of $U*c$ over time at various points in the vicinity of the oscillating cylinder for $A$=0.1m/s and $D$=1e-6

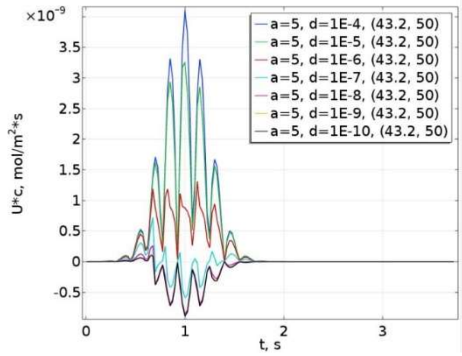
From the Figures it can be seen that the charge concentration changes according to inclination. The impact is higher in the vicinity and decreases significantly at 1 mm from the moving wall. For higher amplitudes (e.g. $A$=5 m/s) the shape of the charge concentrations is distorted. The distortions are not seen at lower amplitudes (e.g. $A$=0.1 m/s). Figures 6 and 7 present the wave forms of the product of velocity magnitude and concentration $U*c$, at the point 2 mm from the oscillating wall for various diffusion coefficients: $D$={1e-4, 1e-5, 1e-6, 1e-7, 1e-8, 1e-9, 1e-10} for the Morlet-type inclination of amplitude $A$=0.1 m/s and $A$=5 m/s, respectively.




Figures 5: Development of $U*c$over time at various points in the vicinity of the oscillating cylinder for $A$=5 m/s and $D$=1e-6



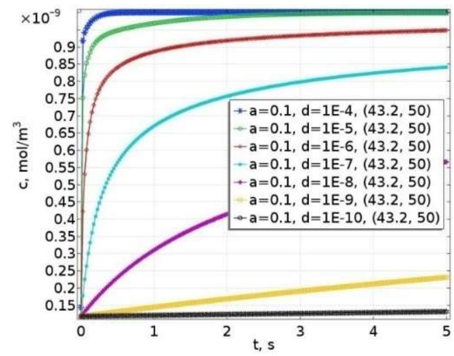

Figures 6: Development of $U*c$ over time at a point in the vicinity-2 mm from the oscillating cylinder for $A$=0.1 m/s and various $D$={1e-4…1e-10}



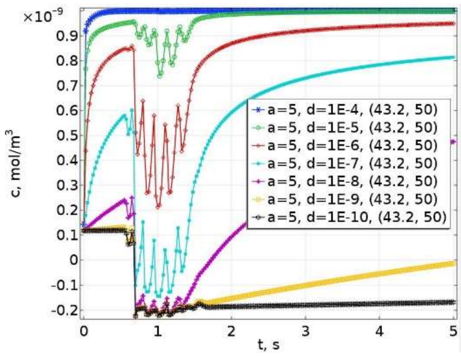

Figures 7: Development of $U*c$ over time at a point in the vicinity-2 mm from the oscillating cylinder for $A$=5 m/s and various $D$={1e-4…1e-10}

Based on the dependencies presented above it can be stated that the impact of diffusion is directly proportional to the resulting charge distribution. For higher amplitudes (e.g. $A$=5 m/s) and diffusions $D$ less than 1e-6 the resulting charge concentration falls below zero. There is no significant difference in the calculated charge concentrations for $D$=1e-9 and 1e-10.

Figures 8 and 9 present the wave forms of concentrations $c$ at various points in the vicinity of the oscillating wall for diffusion $D$=1e-6 for the Morlet-type inclination of amplitude $A$=0.1 m/s and $A$=5 m/s, respectively.

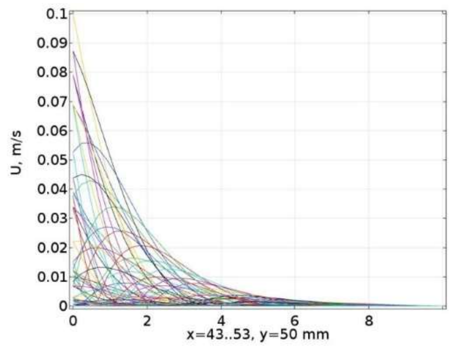



Figures 8: Particle concentration changes overtime at a point in the vicinity-2 mm from the oscillating cylinder for $A$=0.1 m/s and various $D$={1e-4…1e-10}




Figures 9: Particle concentration changes over time at a point in the vicinity-2 mm from the oscillating cylinder for $A$=5 m/s and various $D$={1e-4…1e-10}

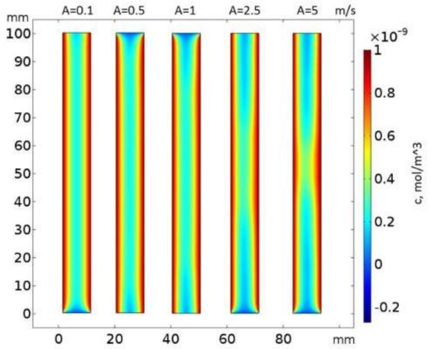
Figure 10 presents the velocity magnitude $U$ calculated along a line in the centre of the object while the inner cylinder was moving according to Morlet-type inclination. The inclination amplitude was $A$=0.1m/s, and diffusion $D$=1e-6. Figure depicts development over time $t$ in the range from 0 to 5 s.




Figures 10: Velocity magnitude along a line in the centre of the object (marked as line $l$ in Figure 2) by inner cylinder movements according to the inclination $A$=0.1m/s, $D$=1e-6, $t_{Morlet}$=0:5 s

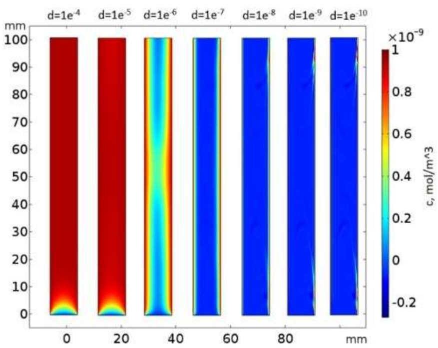
Figure 11 presents the spatial distributions of particle concentration within the analyzed domain at various amplitudes of the inclination at simulation time $t$=0.5 s.

The chosen results correspond to the time when the impact of the oscillating cylinder on the analyzed domain was the highest.
Figures 15 and 16 present the spatial distributions of particle concentration within the analyzed domain at various diffusion coefficients for the Morlet- and Gauss-type inclinations at simulation times *t*=1s and *t*=0.5s and at simulation times *t*=5s and *t*=3s,respectively. The chosen results correspond to the last calculation step. From space distributions of concentrations depicted it can be identified the higher its amplitude the greater the impact range. After the impact of inner cylinder movements decreases the significance of amplitude also disappears.




Figures 11: Particle concentration distribution in the analyzed domain, for inner cylinder moving according to Morlet-type function at *t*=5 s for various amplitudes, diffusion *D*=1e-6

Figure 12 presents the spatial distributions of particle concentration within the analyzed domain at various diffusion coefficients at simulation times *t*=5s. The chosen results correspond to the last calculation step.




Figures 12: Particle concentration distribution in the analyzed domain, for inner cylinder moving at *t*=5 s for various diffusion coefficients *D* and amplitude *A*=5 m/s
The higher the diffusion value, the higher the impact on the charge concentration. For diffusion levels below 1e-7 there is no impact of the oscillating cylinder on the concentration distributions while for values above 1e-6 the impact seems to be too high. Since in measurement results presented in, e.g. (Zmarzły 2012) the impact exists, the diffusion coefficient of 1e-6 was selected as the most reasonable for analyses.
Distortions of the charge density (the product of the concentration and velocity magnitude), which are greater when further from the moving cylinder, are similar to those observed in experiments presented in, e.g. (Zmarzły 2012).

## CONCLUSIONS

The paper considers simulation studies on phenomena of streaming electrification occurring in a modified Couette system filled with transformer oil. The geometry consists of two cylinders: a movable inner and a fixed outer cylinder. Theoretical investigations of the influence of various parameters on the achieved results were performed using numerical simulations. A defined Morlet-type movement of various amplitudes of inclination and various diffusion coefficients were applied and the calculated results were analyzed. The gathered characteristics were compared to experimental signals given in the available literature and similarities were identified. Based on the comparative analysis of the achieved results the following was stated:

- The concentration of charges is not significantly impacted by cylinder movements of low amplitudes, but changes with inclinations of higher amplitudes. The impact is higher in the vicinity and decreases significantly the further from the moving wall. For higher amplitudes the shape of the charge concentrations is distorted for this type of inclination.
- The concentration undergoes the process of equalisation according to the assumed boundaries, but the process is slower the further from the wall.
- The impact area rises with the amplitude of inclination, but it disappears after the movement of the inner cylinder stops.
- The impact of the diffusion coefficient is directly proportional to the charge distribution. For higher amplitudes and diffusions *D*<1e-6 the resulting charge concentration falls below zero. There is no significant difference in the calculated charge concentrations for *D*=1e-9 and 1e-10. The concentration rises over time more slowly for smaller diffusion *D*. The value of *D*=1e-6 was selected as the most reasonable for the analyses due to the gathered data's similarity to the experimental data presented in the literature.

In the future works it is planned to analyse other types of inner cylinder movemnts, e.g. sinusoidal or gaussian.

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**DARIA WOTZKA** received the M.Sc. degree in Computer Science from the Technische Universität Berlin, Germany and the Ph.D. degree in Electrical Engineering from the Opole University of Technology, Poland. She is a lecturer and research fellow at the Opole University of Technology, Poland. Her research interests include digital data processing, modeling and simulation of multiphysical phenomena occurring in electric power devices. Her e-mail address is: `d.wotzka@po.opole.pl`