# Numerical Simulation of Corona Discharge in Compressed Gases with the Effect of EHD Flow

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*Abstract*—**This paper presents the numerical study of the effect of the electrohydrodynamic (EHD) flow on corona discharge in a pin-plate system in compressed gases (one to sixty atmospheres pressure). The electric and gas flow fields are coupled with each other, and were solved simultaneously by employing the commercial CFD FLUENT software. A hybrid numerical algorithm based on the Boundary Element Method, the Finite Element Method and the Method of Characteristics was used to calculate the electrical conditions in the system by solving both the Poisson's and charge transport equations in a two-dimensional model of the problem. This part is written as the User-Defined-Function of FLUENT and the gas flow simulation does not start until the calculation of the electric field is convergent. The electric Coulomb force, responsible for the secondary EHD flow, is calculated and then inserted into FLUENT as flow body force. Finally, the EHD flow, produced by corona discharge, is simulated by solving the Navier-Stokes and the continuity equations. It was found that although the relationship between the normalized corona current and the normalized applied voltage is independent of the operation pressure, the ion convection effect increases with the increase of pressure. Under higher operation pressure the corona current is no longer proportional to the ion mobility, and neglecting the influence of EHD flow on corona discharge can result in significant errors. A high pressure also narrows the drifting region through which the ionic charge travels from the corona electrode to the ground plate.**

## I. Introduction

Compared to a large volume of literature dealing with the corona discharge and EHD flow in atmospheric air, publications related to these phenomena under high-pressure gases are rare. Haidara *et. al*. [1] experimentally observed that the processes of corona discharge in high pressure (0.12-7MPa) air with a point cathode showed a great similarity with those in atmospheric air. The authors verified that the mechanism proposed by Loeb to explain the Trichel regime in atmospheric air for negative point polarity also holds for high-pressure air. Independently on the pressure value, the corona discharge

relies on the avalanche ionization in the high field region near the point and a stabilization effect of the space charge built beyond this ionization region. Behavior of gases at very high pressures can be some extend compared with that of liquids. When electric corona discharge occurs in a dielectric liquid around a blade electrode, the space charge is confined into a thin streak and the EHD flow is in a shape of a plume Higuera [2]. In a similar system, Vázquez *et al.* [3-4] observed that when the velocity of the non-conducting liquid is greater than the ionic velocity, the electric charge is confined into a narrow layer, and the size of the injection zone depends on the shape and size of the discharge electrode and the intensity of the injection strength.

Despite the above-mentioned preliminary experimental observations, no theoretical and numerical investigations of the corona discharge in compressed gases have been found. In this paper, a comprehensive numerical model for simulating the electric corona discharge and the EHD flow in gas under pressure higher than the atmosphere pressure will be developed. The effect of the EHD flow on the corona discharge will be discussed.This year, the ESA papers will not be printed in a proceedings volume. Instead, the papers will be posted on the web as received from the authors. They will be available for viewing or downloading before the meeting, so each attendee can print as many or as few as desired.

## II.  MATHEMATICAL MODEL AND NUMERICAL ALGORITHM

The corona system under investigation consists of two electrodes. The ground electrode is an infinitely large metal plate. The corona electrode is in the form of a sharp hyperboloidal needle with the tip radius of curvature $r_c$=100μm and perpendicular to the ground electrode at a distance of $H$=1cm. By taking into account the axial symmetry of the configuration, a two-dimensional computational model in the cylindrical coordinates ($r, z$) can be assumed, as shown in Fig. 1. The computation domain is defined as $r>=0$.

Based on the assumption that the ionization layer of the corona discharge can be neglected and the unipolar electric charges are assumed to be injected from the corona electrode, the governing equations for the electric field of the corona discharge are the Poisson and charge conservation equations [5]:

$$\nabla^2 \Phi = -\frac{q}{\varepsilon_0} \qquad (1)$$

$$\nabla q(k_i \nabla \Phi + \mathbf{u}) = k_i \frac{q^2}{\varepsilon_0} \qquad (2)$$

where $\Phi$ (V) is the scalar electric potential, $q$ (C/m³)- the space charge density, $\varepsilon_0$ (F/m) - the permittivity of ambient gas, $u$ (m/s) – air velocity, and $k_i$ (m²/Vs) - the ion mobility. In air at atmospheric pressure (760mmHg) and room temperature the ion mobility can be taken as a constant and equal to
$k_{i0}$=1.8~2.2*10⁻⁴m²/Vs. Under actual pressure it becomes,

$$k_i = p_{atm} \times k_{i0} \qquad (3)$$

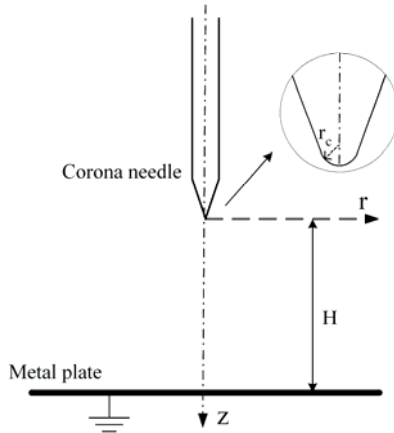where $p_{atm}$ is the actual pressure in atm.



Fig. 1. Two-dimensional computation model for pin-plate system.

Neglecting the gas velocity vector in (2) yields,

$$\nabla q \nabla \Phi = \frac{q^2}{\varepsilon_0} \qquad (4)$$

Under the assumption that the ambient air is incompressible, has constant density and viscosity, the airflow has to satisfy the continuity and the conservation of momentum equations [5]:

$$\nabla \cdot \mathbf{u} = 0 \qquad (5)$$

$$\rho_f[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}] = -\nabla P + \eta \nabla^2 \mathbf{u} + \mathbf{F} \qquad (6)$$

where $\rho_f$ (kg/m$^3$) is the gas density, $P$ (Pa) - the static pressure, $\eta$ (kg/ms) - the air viscosity, and $F$ (N/m$^3$) - the body force, in this case equal to the Coulomb force $q\nabla \Phi$. The gas density is proportional to the actual pressure and the viscosity is kept constant.

The numerical model governed by (1), (2), (5) and (6) is called fully coupled model, while the one governed by (1), (4), (5) and (6) is called decoupled model. In fully coupled model, the gas flow velocity vector appears in corona discharge governing equation (2) and the space charge density and electric field are included in the flow governing equation (5), therefore, both electric and flow fields are mutually coupled with each other. However, for decoupled model only one-way coupling is necessary: electric forces cause gas motion, but charge convection is neglected.

The boundary conditions for the electric potential are straightforward: a constant DC potential is applied on the corona electrode and zero on the ground electrode. An indirect boundary condition for space charge density is obtained by adopting the Kaptzov hy-
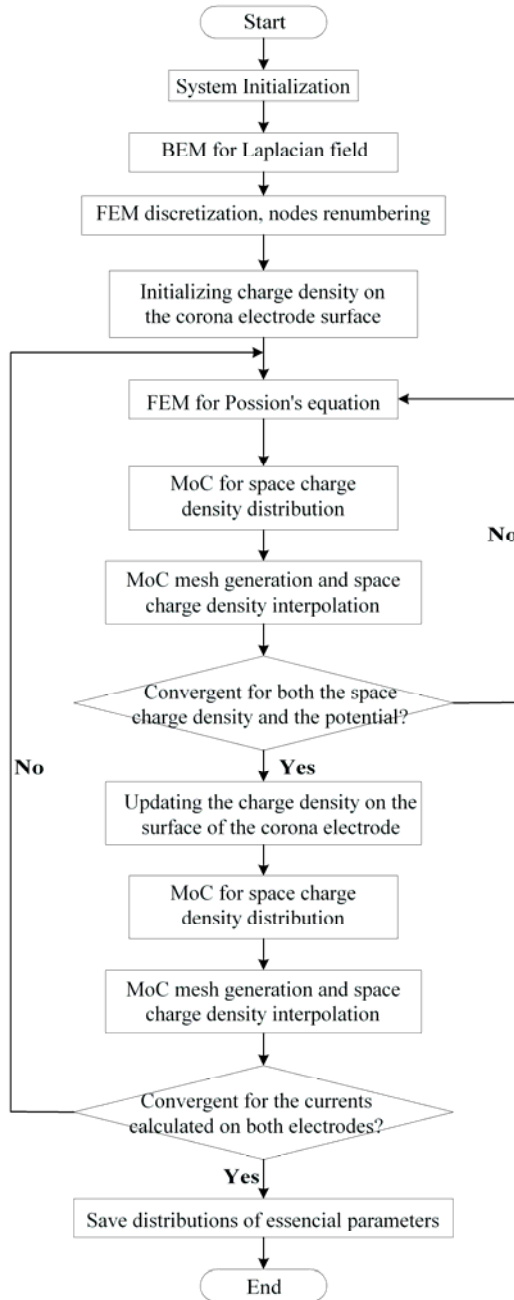
Fig. 2 Flow chart of the corona simulation program

pothesis, which suggests that the electric field increases proportionally to the applied voltage below the corona onset, but it remains at the same level after the corona is initiated [6]. This critical electric field on the surface of corona electrode is given by the experimental Peek's value [7],

$$E_0 = 3.1 \cdot 10^6 \cdot p_{atm}(1 + \frac{0.308}{\sqrt{0.5 \cdot p_{atm} \cdot r_c}}) \qquad (7)$$

where $r_c$ is the radius of curvature of the corona electrode in cm.

In the flow field, surfaces of both electrodes are defined as the stationary walls where velocity vectors vanish. The open boundary is defined as the pressure outlet.

A hybrid technique based on the combination of Boundary Element Method (BEM), Finite Element Method (FEM) and the Method of Characteristics (MoC) has been used to solve the corona problem. The whole algorithm is arranged into two iterative loops. In the inner loop, for assumed space charge density on the corona electrode surface, governing equations for the electric field and space charge density are solved iteratively until convergence is reached in the whole calculation domain. In the outer loop, the charge density on the corona wire surface is continuously updated using

$$q_{0new} = q_{0old} + \alpha(E - E_0) \qquad (8)$$

where $\alpha$ is an experimentally found coefficient, $q_{0old}$ is the old value used in the previous iteration and $q_{0new}$ is the new estimate at the present iteration, until convergence is reached for the electric currents calculated on both electrodes. The structure of the corona simulation program is depicted in the flow chart in Fig. 2.

Meanwhile, the commercial software FLUENT was employed for the calculation of the gas flow. The corona simulation program was coded as a User-Defined-Function (UDF) of FLUENT and the Coulomb force was inserted into FLUENT as the gas body force. The air flow governed by (5) and (6), which has been modified by EHD, is simulated using the finite volume method (FVM). After the residuals of both velocity components, the turbulence kinetic energy ($k$), and its rate of dissipation ($\varepsilon$) satisfy the specific tolerance, the flow simulation process terminates. The air flow velocity is then entered back into the corona simulation program by using MoC, which makes the whole simulation algorithm a triple iterative loop. The above-mentioned process is repeated, as shown in Fig. 3, until convergence is reached for all essential electrical and flow parameters. This stage of calculation can provide detailed information on the airflow, such as stream functions, path lines, velocity and pressure distributions, etc.
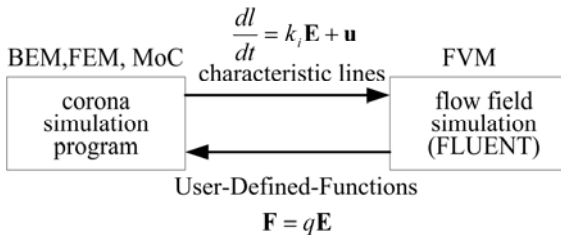


Fig. 3 Schematic calculation procedure for fully coupled model.

III.   SIMULATION RESULTS

The normalized relationship between the applied voltage and the corona current has been shown in Fig. 4. All three curves calculated at 50 atm pressure and one atm pressure, respectively, have the same trend with the corona current rising above the onset level approximately as a square function of the applied voltage. This proves the experimental observation obtained by Haidara *et al.* that the relationship between the applied voltage and the corona current at atmospheric pressure holds for higher pressures, too [1]. There-fore, any conclusions deduced from this relationship are also suitable for higher pres-sures. A noticeable difference between the two curves calculated at 50 atm pressure by using the decoupled and fully coupled models can be observed. The difference between both curves increases with the increase of the applied voltage. This phenomenon con-firms that at pressures higher than atmospheric one the effect of EHD flow on corona discharge becomes significant and should be considered, although at atmospheric pres-sure an opposite conclusion has been drawn [5].

Besides the classic time-of-flight method for measuring mobility of the charged spe-cies in gases [8,9], a possible alternative method based on measurement of the unipolar corona discharge current from a sharp needle electrode was suggested by some authors [10,11]. The simple idea in this technique is that the corona current is proportional to the ion mobility. It has been pointed out that this method has some advantages over the tradi-tional one when dealing with the gases in a large range of pressures above the atmos-pheric one [11].  However, results from Fig. 4 prove that at high pressures, the ion con-vection plays an important role in building up the corona current and the current is no longer proportional to the ion mobility. Therefore, the use of the total current method for estimation the ion mobility at high pressures can lead to signification errors.
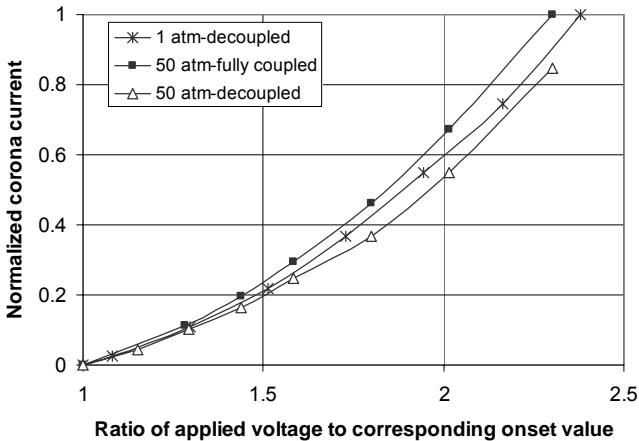


Fig. 4. Normalized corona current versus normalized applied voltage at different pressures with decoupled and fully coupled models.

The current density distributions on the ground electrode at 50 atm pressure obtained for the fully coupled model are shown in Fig. 5. A higher applied voltage results in a

higher current density for the same radial coordinate and a larger target area of the drifting ions deposition on the ground electrode. This is because the higher applied voltage requires higher space charge density in the air gap to keep the electric field on the corona electrode surface at the constant Peek's value. This can be achieved if the space charge density increases as well as the charge cloud spreads more in the radial direction.
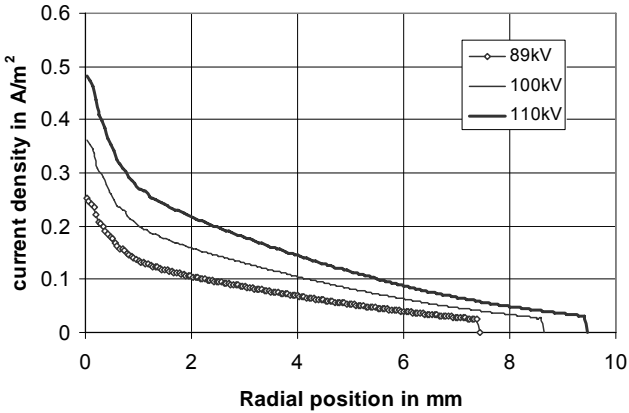


Fig. 5. Current density on the ground plate at different applied voltages at 50 atm pressure.
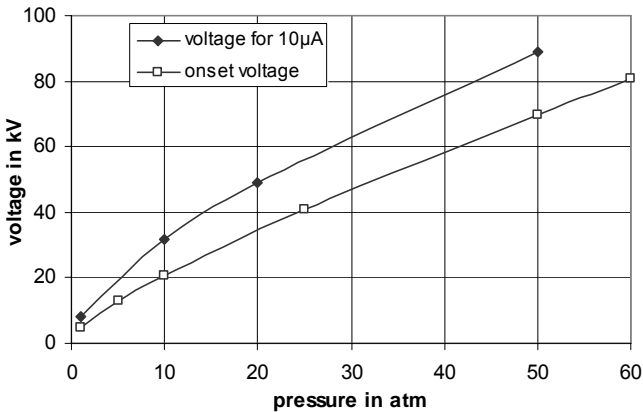


Fig. 6. Onset voltages and voltages for the same corona current of 10 μA at different pressures

The relationship between the corona onset voltage and the gas pressure is shown in Fig. 6 for pressures changing from 1 atm to 60 atm. The onset voltage increases with the increase of the pressure. For this reason, investigating the effect of the operation pressure on the corona discharge based on a constant applied voltage is not reasonable. At the same voltage level the gas breakdown (spark) may take place at a lower pressure while for a higher pressure the corona discharge may not start yet. Therefore, an alternative way of having a constant corona current should be considered. In order to generate an equal corona current of 10 μA, the applied voltage should increase significantly with the pressure (this relationship can also be found in Fig. 6). The curve initially has a relatively steep slope, but then it tends to decrease when the operation pressure increases. This is

because at the higher pressures, the effect of the ion convection becomes more significant and contributes more to the corona current.
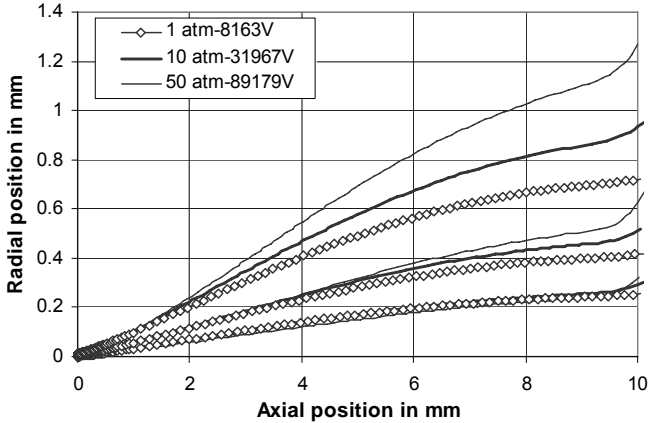


Fig. 7. Ion trajectories close to the axis of symmetry at different pressures and voltages assuming a constant corona current of 10 µA.



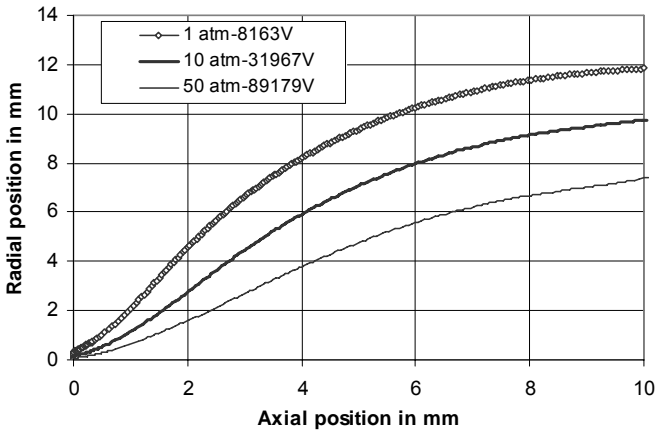Fig. 8. Outer ion trajectories at different pressures and voltages assuming a constant corona current of 10 µA.

The ions injected from the identical point on the corona electrode surface travel along different trajectories and are deposited at different locations on the ground electrode at different operation pressures. Fig. 7 displays the trajectories originated from the points close to the corona electrode tip. At higher pressure they tend to bend away from the axis of the symmetry and into the radial direction when approaching the plate. This is because at higher pressures, the decreased ion mobility, along with the lower electric field in the region close to the plate, results in smaller ion drift velocity in the axial direction. In the same area, the EHD flow in a radial direction becomes relatively large when compared

with axial ion drift velocity. This confirms again the non-negligible effect of ion convection at higher pressures. The outer trajectories for three different pressures have been presented in Fig. 8. Since they mark the boundary where no space charge exists outside, it is clear that the ion cloud shrinks with the increase of the pressure. Under high pressures the EHD flow compresses the space charges towards the axis of the symmetry forming a narrower jet.

- The current density distributions on the ground plate for different gas pressures are shown in Fig. 9. A higher pressure causes in a smaller target area of the drift ion deposition on the ground plate and a higher current density. These features indicate again that the ion cloud shrinks with the increase of the pressure.
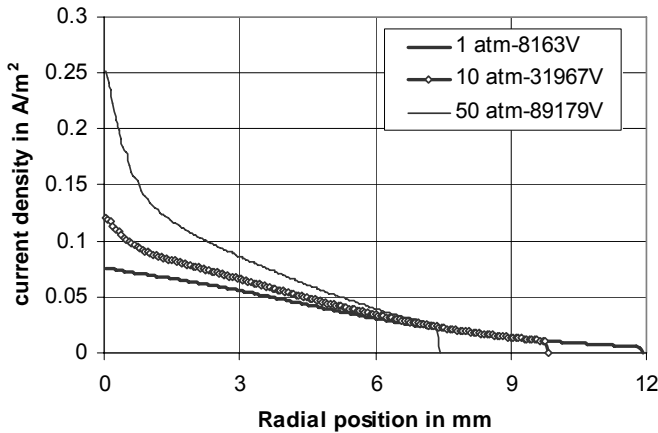


Fig. 9. Current density on the ground plate at different pressures assuming a constant corona current of 10 µA.

### IV. CONCLUSION

The effect of EHD secondary flow on the characteristics of corona discharge in a pin-plate system for different values of the gas pressure (1 atm to 60 atm) has been discussed. The higher pressures result in lower ion mobility, lower ion drift velocities, and eventually a stronger ion convection effect. Thus, for compressed gases the fully coupled model has to be used, even tough there is no external airflow. Changing the pressure not only changes the property of the gas but also affects the corona onset conditions. Therefore, the results have to be compared for the same corona current (in this case, equal to 10 µA) rather for the same applied voltage. The following conclusions can be drawn from the presented results:

- In compressed gases, the ion convection effect increases with the increase of pressure, and neglecting the influence of EHD flow on corona discharge can result in significant errors.
- The relationship between the normalized corona current and the normalized applied voltage is independent of the operation pressure.

- Higher pressure not only compresses the gas and changes its properties, but also narrows the drift region through which the ionic charge travels from the corona electrode to the ground plate.
- In order to have the same corona discharge current at higher pressure, higher voltage has to be applied.

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