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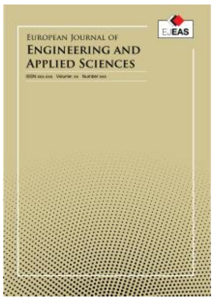

Research Article

Dynamics of Charging of Dielectric Liquid Drops in a Corona Discharge Field

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Abstract: The development of innovative electrojet technologies based on the formation of sequential flows of monodisperse droplets in the working environment remains among the current problems today. In this study, it has been determined that in the “needle-plane” electrode system where corona discharge occurs. The charging kinetics of spherical particles are investigated in this system. These particles were created under equal conditions for various dielectric liquids. The spherical particles had different radii and different relative dielectric permittivities. The study determined that the charging kinetics of these particles differ. This difference depends on the polarity of the small radius electrode. In particular, the effective ionization coefficient in an electronegative gas environment (e.g. in air) where corona discharge occurs, it has been shown that when the needle electrode has a negative polarity, the amount of charge accumulated on the spherical particle is higher compared to the positive polarity case.

Keywords: *Attachment coefficient, Corona discharge, Townsend ionization coefficıent,*

Korona Deşarj Alanında Dielektrik Sıvı Damlacıklarının Yüklenme Dinamiği

Öz. Çalışma ortamının monodispers damlacıklarının ardışık akışlarının oluşumuna dayanan yenilikçi elektrojet teknolojilerinin geliştirilmesi günümüzde güncelliğini koruyan problemler arasında yer almaktadır. Bu çalışmada, korona boşalmasının gerçekleştirildiği “iğne- düzlem” elektrot sisteminde, küçük yarıçaplı elektrotun polaritesine bağlı olarak, incelenen dielektrik sıvılar için eşit koşullarda oluşturulan farklı yarıçaplara ve farklı bağıl dielektrik geçirgenliklere sahip küresel parçacıkların yüklenme kinetiğinin farklılık gösterdiği tespit edilmiştir. Özel durumunda, korona deşarjının gerçekleştirildiği bir elektronegatif gaz ortamında (örneğin hava ortamında) etkin iyonlaşma katsayısının da dikkate alınmasıyla, iğne elektrotun negatif polariteye sahip olması durumunda küresel parçacık üzerinde biriken yük miktarının pozitif polarite durumuna göre daha yüksek olduğu gösterilmiştir.

Anahtar kelimeler: *Bağlanma katsayısı, Corona boşalması, Townsend iyonlaşma katsayısı.*

1. Introduction

Electro-droplet equipment and technologies are based [1,2,5,9] on the creation (using microprocessors or microcomputers) of a linear sequence of a flow of monodisperse drops of working fluid. Up to a hundred thousand of such drops per second can be formed on one nozzle, and of the same diameter - about tens, hundreds of micrometers, located at the same distance from each other. In this case, it is possible to communicate a given value of electric charge of one sign or another to a drop of working fluid and, thus, to deflect this drop in an electric field

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to a given point, determined by the technological process.

The characteristic features and advantages of electro-droplet jet technologies are:

- absence of moving mechanical elements moving with friction in the devices implementing them;

- microprogram control of the processes of obtaining a linear flow of monodisperse drops of working fluid with the same distance between the drops, the message controlled both by the magnitude and by the sign of the electric charge of the drops, their deviation in the electric field, which ensures flexibility of control;

- contactless application of working fluids, charged and uncharged, to objects with any surface shape made of various materials (chemical threads, fabrics, plastics, glass, metal, ceramics, paper, etc., etc.).

The article examines the process of imparting an electric charge to drops of dielectric working fluids in the electric field of a corona discharge. This method [5,7] is based on the phenomenon of the emergence of a unipolar ion flow in the outer zone of a corona discharge, which occurs in electronegative gases and their mixtures (such as air) in a sharply non-uniform electric field.

The aim of this work is to investigate the dynamics of charging of droplets of different sizes for dielectric liquids with different relative permittivity in the field of negative and positive corona discharge.

Based on Potenier's formula for the electric charge imparted to a drop of dielectric liquid in a corona discharge field, a simple expression for the rate of field charging of a spherical particle is derived. It should be emphasized that with a decrease in the radius of curvature of the corona-forming needle electrode, the corona discharge used to impart an electric charge to drops of dielectric liquids occurs at a lower voltage on the electrodes.

2. Theory

A corona discharge in gases occurs at a certain, so-called initial, electric field strength E_{cn} in the immediate vicinity of a needle electrode when high voltage is applied to needle-plane type electrodes.

The initial electric field strength E_{ci} of a corona discharge is found from the condition of the self-sufficiency of a corona discharge in electronegative gases and their mixtures [2,3,4,6]

$$\int_0^{l_k} \alpha_{eff} dx = ln\left[\frac{(1+\gamma_i)}{\gamma_i}\right] \cong K = Const \quad (1)$$

when the inequality is satisfied in the inner region of the corona discharge

$$\alpha_{eff} = \alpha - \eta \quad (2)$$

Here α_{eff} is the effective impact ionization coefficient, which determines the process of electron multiplication in the corona layer during impact ionization;

α is the coefficient of impact ionization by electrons (the first Townsend ionization coefficient), which determines the number of ionizations by electrons per unit path during their movement in an electric field along the lines of force. Numerically, this coefficient is equal to the product of the number of collisions per unit path of an electron with gas molecules and the probability that these collisions will end in ionization and depends on the ratio of the electric field strength E to the gas pressure p [3,4]. η is the attachment coefficient, which characterizes the process of formation of stable negative ions in the corona layer due to the addition of an extra electron by gas atoms and molecules, which already loses the ability to ionize [2,5,6].

γ_i is the generalized secondary ionization coefficient, which characterizes the average number of electrons formed within the corona layer as a result of secondary ionization processes;

l_k is the length of the lines of force within the corona layer; x is the path from the cathode of the electron avalanche.

Fulfilment of condition (2) corresponds to the so-called threshold value $(E/p)_{cr} = b$, and, consequently, a self-sustained discharge in a gas is possible only at $E/p \geq b$ [2-6].

When implementing the method of imparting a unipolar electric charge to drops of dielectric liquids in a corona discharge field, the distances h between the needle-plane type electrodes are relatively small (no more than tens of mm), and the radius of curvature of the needle electrode r_0 is from $5 \cdot 10^{-2}$ to $10 \cdot 10^{-2}$ mm.

Based on the studies conducted for the applications considered in the work, a formula was obtained for the initial electric field strength of the occurrence of a corona discharge E_{ci} which gives good agreement between the calculation results and the experimental results in the above-mentioned range of changes in h and r_0, the fundamental difference of which from the known ones is that it takes into account the dependence of E_{ci} on the distance h between the electrodes [2- 6].

$$E_{ci} = A\delta_0 + B \cdot \left(\frac{h\delta_0}{r_0}\right)^{0,5} \quad (3)$$

where, $A = \frac{bp_0T}{T_0}$; $b = \left(\frac{K}{ab_1\delta_0}\right)^{0,5}$

The coefficients a and b are found from the expression $\frac{\alpha_{eff}}{p} = a\,[(E/p) - b]^2$ near the threshold value $(E/p)_{a}$, at which the condition (2) of the corona discharge independence is satisfied. The relative density δ_0 of gas (air) is characterized by the expression $\delta_0 = \frac{p\,T_0}{p_0\,T}$ where $p,\ p_0$ are the absolute current pressure and the pressure of gas (air), respectively, under normal atmospheric conditions ($p_0 = 101{,}3$ kPa, $T_0 = 293$ K); T, T_0 are the absolute temperatures of gas (air) at p and p_0, respectively. The coefficients a, b are found experimentally for a given type of gas, electrode configuration and the nature of the voltage on them.

The coefficient K is determined from the condition (1) of the independent corona discharge in air; b_1 is an empirical coefficient characterizing the distance from the electrode with a small radius of curvature r_0, within which, before the moment of occurrence of the corona discharge, the electric field near the threshold value E/p has a pronounced non-uniformity along the length of the interelectrode gap (maximum gain).

Therefore, this influence can be neglected. For coaxial electrodes, formula (3) can be rewritten as [1-6].

$$E_{ci} = A\delta_0 + B \cdot \sqrt{[(R/r_0) - 1]\delta_0} \quad (4)$$

where R is the radius of curvature of the non-corona electrode.

Calculations of E_{ci} using expression (4), obtained from (3), most accurately coincide with experimental data in the entire range of possible curvature radii $r_0 = (5-10) \cdot 10^{-2}$ mm of corona electrodes for coaxial cylinders at such small interelectrode distances when the internal region of the corona discharge, where $\alpha_{eff} > 0$, becomes commensurate with the distance between the electrodes [6].

Calculations using the formulas of Pick, Townsend, Lesch, Alexandrov, Engel and Steenbeck, which do not take into account the dependence of E_{ci} on the distance between the electrodes at such small interelectrode gaps, give large discrepancies with the experimental data [6].

The value of the initial corona voltage U_{ci} for coaxial electrodes is determined from (4) using the formula

$$U_{ci} = E_{ci}\, r_0\, ln(R\,/\,r\,) \quad (5)$$

Based on Potenier's formula for the electric charge communicated to a drop of dielectric liquid in a corona discharge field, we obtain [7-14]

$$q(t) = \frac{12\pi\varepsilon_0\varepsilon_1\varepsilon_2 r^2 e n_0 \mu E_c}{(4\varepsilon_0 + en\mu t)(\varepsilon_1 + 2\varepsilon_2)} t \quad (6)$$

where $\varepsilon_0 = 8{,}85 \cdot 10^{-12}$ F/m is the vacuum permittivity (electric constant); ε_1 is the relative permittivity of the liquid; ε_2 is the relative permittivity of the medium surrounding the dielectric liquid droplet (for gases $\varepsilon_2 = 1$); r is the radius of the dielectric working fluid droplet, m; $e = 1{,}6 \cdot 10^{-19}\ C$ is the electron charge; n_0 is the average ion concentration over the entire interelectrode gap; μ is the ion mobility, $m^2/(V \cdot s)$; E_{ca} is the average electric field strength in the interelectrode gap during corona discharge, V/m; n is the electron concentration in the corona discharge field; t is the time the dielectric liquid droplet remains in the corona discharge field.

Expression (6) can be rewritten as

$$q(t) = \frac{en_0\mu t}{(4\varepsilon_0 + en\mu t)} \cdot q_{max} \quad (7)$$

where

$$q_{max} = \frac{12\pi\varepsilon_0\varepsilon_1\varepsilon_2 r^2 E_{cr}}{(\varepsilon_1 + 2\varepsilon_2)} \quad (8)$$

− maximum electric charge of a drop of dielectric working fluid in a corona discharge field.

Based on the Potenier formula, the dynamics of the electrification of dielectric liquid droplets of different diameters and different permittivity was investigated. The corresponding dependences of the electric charge imparted in the field of a corona discharge to a drop of dielectric liquid as a function of the radius of the drop, the dielectric constant of the liquid, the mobility of unipolar ions with negative and positive corona, as well as the average electric field strength in the interelectrode gap are obtained.

All dependencies are obtained for the most realistic case of imparting an electric charge to drops of dielectric working fluids when implementing electro-droplet technologies, when a corona discharge occurs in the air between needle-plane type electrodes.

In this case, the average concentration of ions across the entire interelectrode gap during a corona discharge in accordance with [1-3] will be $n_0 = 10^{14}\ ion/m^3$. Therefore, as a first approximation, taking in (6) $n_0 = n = 10^{14}\ ion/m^3$, we rewrite the expression for air as

$$q(t) = \frac{533{,}82 \cdot 10^{-17} \cdot \varepsilon_1 \cdot r^2 \cdot \mu \cdot E_{cr}}{(35{,}4 \cdot 10^{-12} + 1{,}6 \cdot 10^{-5} \cdot \mu \cdot t)(\varepsilon_1 + 2)} t \quad (9)$$

Let us consider a method of imparting a negative electric charge to the drops at a negative potential of the needle electrode. In this case, a unipolar flow of negative ions will arise in the outer region of the corona discharge. The mobility of negative ions in air [3] $\mu^- = 1{,}8 \cdot 10^{-4}\ \ m^2/V \cdot s$.

Then expression (10) is rewritten as

$$q(t) = \frac{960{,}87 \cdot 10^{-21} \cdot \varepsilon_1 \cdot r^2 \cdot \mu \cdot E_{cr}}{(35{,}4 \cdot 10^{-12} + 2{,}88 \cdot 10^{-9} \cdot t)(\varepsilon_1 + 2)} t \quad (10)$$

3. Results and Discussions

Figures 1–3 show the results of studies of imparting a negative electric charge to droplets, that is, in the field of a negative corona discharge in air.

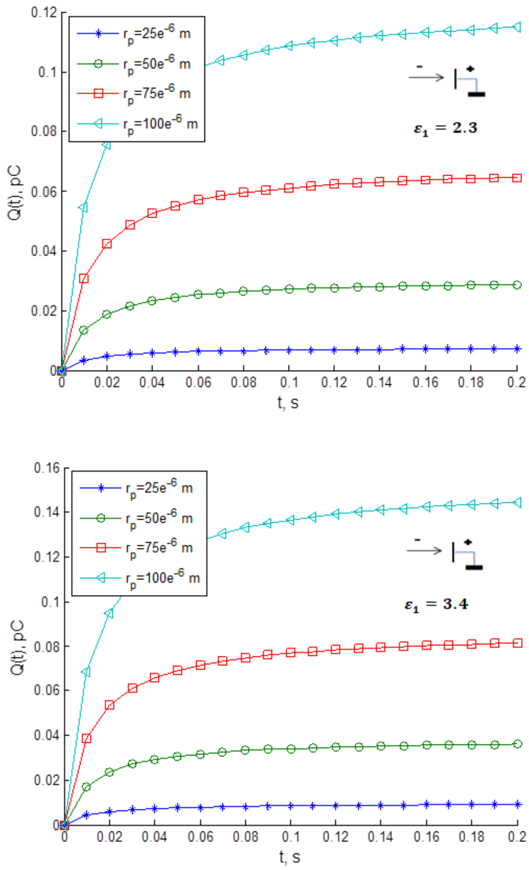


Figure 1. *The charging dynamics of droplets of different sizes in the field of a negative corona discharge with a relative permittivity of dielectric liquids of* $\boldsymbol{\varepsilon_1 = 2{,}3}$ *;* $\boldsymbol{\varepsilon_1 = 3{,}4}$ *;* $\boldsymbol{E_c = 10^5\ V/m}$

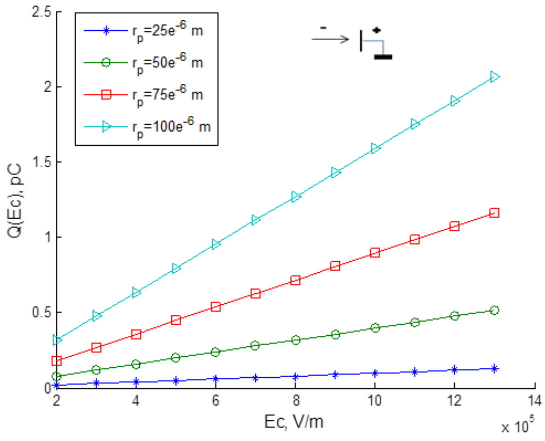


Figure 2. *Effect of the negative corona discharge field strength on the droplet charge at* $\boldsymbol{t = 0,1s}$ *and* $\boldsymbol{\varepsilon_1 = 2.3}$

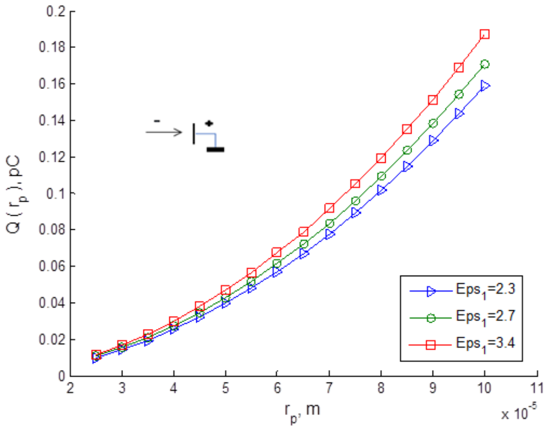
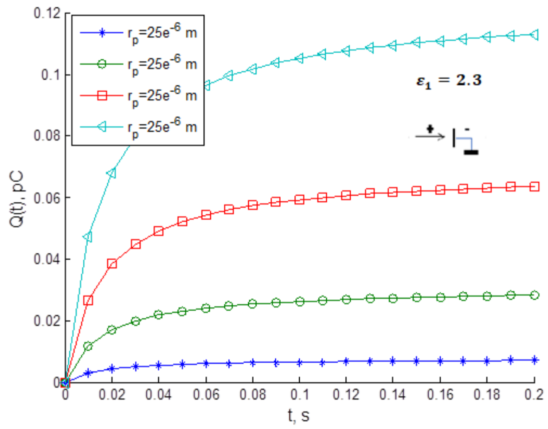


Figure. 3. *The influence of the droplet radius and dielectric constant on their charge in the field of a negative corona discharge at* $\boldsymbol{t = 0,1s}$, $\boldsymbol{E_c = 10^5\ V/m}$



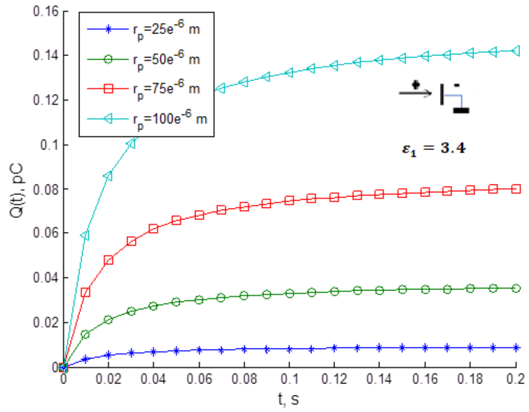


Figure 4. *The charging dynamics of droplets of different sizes in the field of a positive corona discharge with a relative permittivity of dielectric liquids of* $\boldsymbol{\varepsilon_1 = 2,3}$; $\boldsymbol{\varepsilon_1 = 3,4}$; $\boldsymbol{E_c = 10^5\ V/m}$

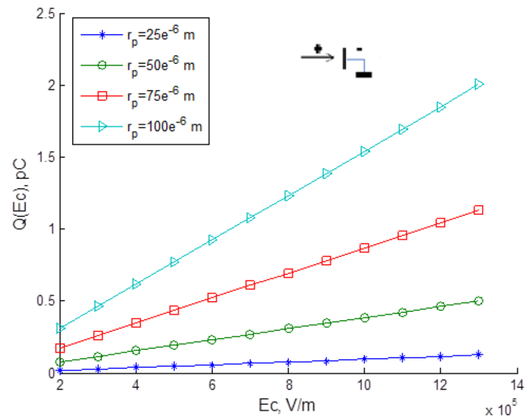


Figure 5. *Effect of positive corona discharge field strength on droplet charge at* $\boldsymbol{t = 0,1s}$ *and* $\boldsymbol{\varepsilon_1 = 2,3}$

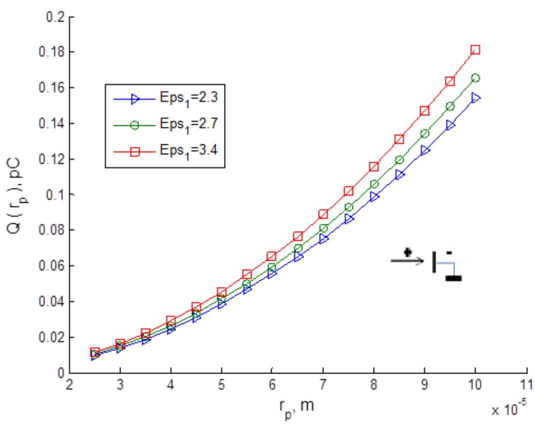


Figure 6. *The influence of the droplet radius and the dielectric constant of liquids on the charge of drops in the field of a positive corona discharge at t = 0.1 s,* $\boldsymbol{E_c = 10^5\ V/m}$

To impart a positive electric charge to the drops, a positive potential is applied to the needle electrode. The mobility of positive ions in air $\boldsymbol{\mu^+ = 1,4 \cdot 10^{-4}}$ $\boldsymbol{\frac{m^2}{V} \cdot s}$ [2,3] Then expression (10) is rewritten as

$$\boldsymbol{q(t) = \frac{747{,}35 \cdot 10^{-21} \cdot \varepsilon_1 \cdot r^2 \cdot \mu \cdot E_{cr}}{(35{,}4 \cdot 10^{-12} + 2{,}24 \cdot 10^{-9} \cdot t)(\varepsilon_1 + 2)} t} \quad (12)$$

In Figs. 4–6, in accordance with (12), the results of studies of imparting a positive electric charge to drops are presented.

4. Conclusions

Based on the results obtained within of the statement problem, the following conclusions can be drawn:

–regardless of the polarity of the unipolar ion flow created in the outer region of the corona discharge (the polarity of the tip), drops of various diameters acquire an electric charge equal to $\mathbf{95\%}$ of their maximum value during a time of $\boldsymbol{(0,12 – 0,15\ )s}$ in the corona discharge field. Consequently, when implementing electro-droplet jet technologies (liquids), the length of the interelectrode gap should be selected accordingly;

– it is possible to easily regulate the sign and magnitude of the electric charge imparted to the drops by changing the polarity of the corona-forming sharp electrode and the voltage value on the electrodes, and the larger the drop diameter, the greater the electric charge imparted to it;

-with a negative corona for the selected type of dielectric liquid, a drop of the same diameter at the same electric field strength acquires an electric charge greater in magnitude than with a positive corona. At the same time, the range of voltage variation on the electrodes up to the spark breakdown of the interelectrode gap expands (at the selected distances between the corona electrodes);

– the greater the relative permittivity of the working dielectric liquid, the greater the magnitude of the electric charge imparted to the droplet at the same voltage and polarity on the electrodes and the selected interelectrode gap.

Author Contribution

Data curation - Hafiz Alisoy (HA), Hasan Demir (HD), Gülizar Alisoy (GA); Formal analysis - (HA, HD, GA); investigation - (HA, HD, GA); Experimental Performance - (HA, HD, GA); Data Collection - (HA, HD, GA); Processing - (HA, HD, GA); Literature review - (HA, HD, GA); Writing - (HA, HD, GA); Review and editing - (HA, HD, GA)

Declaration of Competing Interest

The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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