Charge transfer evaluation in solid insulating materials encapsulating the gaseous voids of submillimeter dimensions using transmission line method

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Abstract: In this work, using a lumped RC circuit model which is based on transmission line modeling (TLM) method, the charge transfer in a solid insulating system encapsulating a gaseous void of submillimeter dimensions is evaluated. Here, both the dielectric material and gaseous void are considered simultaneously as a transmission line. The transmission line includes the capacitive and resistance elements and, the obtained circuit equations were coupled with the continuity and kinetic energy equations for charged species along with Poisson’s equation. These equations are solved via 4th order Runge-Kutta method and, the electric field and potential, density of all the charged species, discharge current and electron temperature are calculated in the gaseous media. Hence, the discharge propagation in the gaseous void and its mutual influences on dielectric medium are described. The partially penetration of electrons in the avalanche head into the anode dielectric bulk is shown, and it is observed that their movements towards the electrodes are much faster than ions. Besides, the total transferred charge particles at both the avalanche and streamer phases in the void is calculated. Besides, it was found that, the electrons temperature distribution completely influenced by electric field in the gaseous void. In addition, the effects of voids thickness and their location on the discharge current are examined. It is shown that, at the higher void thicknesses and for the cavities locating in the electrodes adjacent, the magnitude of discharge current increases.

Key words: Solid insulating materials, voids of submillimeter dimensions, charge transfer, TLM method

1. Introduction
It is widely known that the space charges are generally deposited into the solid insulating materials either from the metallic electrodes or activity of electrical discharges in the voids of submillimeter dimensions that are encapsulated within these materials. However, to have a complete understand about the partial discharge mechanism in the voids of submillimeter dimensions, it is necessary to perform a comprehensive study based on the microscopic charge distribution [1].

These unfavorable phenomena will normally lead to the unrecoverable damages into the bulk of solid insulators. So far, a number of experimental and theoretical studies are performed on the transport of space charge in the solid insulating materials that are consisting of voids of submillimeter dimensions and tree tubules [2].

Wang et al. studied the space charge transport mechanism at the solid-gas interfaces forming between the solid dielectrics and dry air, nitrogen, and carbon dioxide at the atmospheric pressure and under the impulse...
high applications. They obtained the required breakdown time and voltage for all the solid-gas interfaces on the application of both the high voltage negative and positive impulses [3].

In a developed numerical model by Ghassemi et al., the dielectric barrier effects on the charge transfer in a gaseous discharge medium including a dielectric layer between the two metallic plates were examined. The transport of different charged particles in the gaseous and dielectric media along with the surface reactions were simulated using the continuity and Poisson’s equations. Using this model, the maximum withstand voltage for the insulating systems consisting both the gaseous and solid dielectrics was predictable [4]. Their model, however, was incapable of simulating the different gas discharge stages such as the electron avalanche and streamers propagation processes.

Mahdipour et al. used a numerical model for PD pulses in the spherical voids encapsulating within the solid insulating part of power cables. The obtained equations were solved using the finite element method (FEM), and it was shown that, the actual charge which is transferred to the gaseous medium is sum of the apparent and stored charges in the void before PD initiation. Besides, it was observed that, at the higher distances of void from the center of cable, the PD pulses magnitude reduces while the inception voltage was increased [5]. In this model, while the circuit model was taken into the account, the continuity equations for charge carriers were absent. Hence, it is incapable of performing a comprehensive analysis on the discharge phenomenon such as the temporal variations electrons and ions densities.

Tewari at al. tried to understand the charge transport mechanisms in the gas-solid interface in the high voltage devices. They used the finite difference time domain (FDTD) to solve the governing equations which was based on the particle in cell-Monte Carlo collision computations (PIC-MCC) scheme. Using the obtained results, net charge density in the gaseous medium was studied. Moreover, the dielectric influences on the charge transport characteristics were examined [6].

Using a mathematical model, Serdyuk et al. [7] simulated the charge transfer process in a polyethylene material. It was including a void of submillimeter dimensions that was inserted between the two metallic electrodes. The spatiotemporal variations of space charges in the entire of insulating system encapsulating a gaseous medium were analyzed. Moreover, the influences of the charged particles deposition from the gaseous medium into the bulk of solid insulating material on the charge transport and accumulation were studied. Besides, the effects of charge transport and accumulation on the distortion of electric field profile inside the solid dielectric were examined [7]. In spite of the significant influences of temperature on the conductivity and electric field distributions [8], their model was incapable of electrons temperature calculation during the charge transfer in the gaseous discharge media.

So far, a plenty of experimental and theoretical efforts are carried out to examine the various physical and technical aspects of the gas discharges in the presence of solid insulating materials. However, a comprehensive numerical model to perform an extensive study on the charge transport in the solid insulating materials encapsulating the gaseous voids is still absent. This model must be able to provide the necessary information for the development, optimization and coordination of the solid insulation systems in their practical applications in the high voltage devices. Besides, till now, the dependency of insulation conductivity on the field and temperature is not taken into consideration. To this end, in the present work, a lumped circuit model based on RC elements is developed to describe the dynamics of charge transfer in a solid insulating system containing the dielectric materials encapsulating a void of submillimeter dimensions. Hence, in this paper, a transmission line modeling (TLM) method is used to develop a numerical model which is able to examine the various physical and technical parameters of the considered solid insulating system such as electric field and potential,
density of all the charged species, discharge current and electron temperature. Moreover, the influences of insulators conductivity on the electric field and temperature distributions under HVDC application will be discussed. Due to the nature of the TLM method, electric field calculation is easier compared with the other numerical procedures. Besides, using this method, the charge accumulation effects causing from the previous avalanches on the current characteristics, cavity voltage and the spatial distribution of the electric field are studied. Furthermore, the gas discharge propagation phases including the electron avalanche and streamer formation are analyzed. Finally, the obtained numerical results will be compared with the theoretical and experimental results in the literature.

2. Model description

In this work, to model a solid insulating material encapsulating a void of submillimeter dimensions under high voltage application, an air gap is placed between the two metallic electrodes covering with the solid dielectric slabs, as shown in Figure 1. The spatial distance of 4 mm is considered between the metallic electrodes including the air gap with the thickness of 3 mm. The thickness of each solid dielectric barrier is assumed to be 0.5 mm. Initially, the charges injection process occurs in the unipolar forms on the metal-dielectric interfaces. Moreover, the developed numerical model is able to describe the electron avalanche in the gaseous medium based on the application of external high voltage on a solid insulating material encapsulating a void of submillimeter dimensions. Hence, the spatial and temporal variations of charged carriers density, electric potential and field, resistance, conductivity, etc., can be obtained using the continuity and Schottky’s equations in the gaseous media. To this end, the entire of insulating system is taken as a transmission line with the resistive and capacitive elements. Hence, the obtained two-dimensional circuit equations from the TLM method are coupled with the continuity equations for the charged carriers in both media.

Figure 1. The model geometry for a solid insulating material encapsulating a void of submillimeter dimensions.

As depicted in Figure 1, an air-gap is assumed between the metallic electrodes that are covered with the solid polymeric layers (here, LDPE). The high voltages of $V_c$ and $V_a$ are applied on the cathode and anode electrodes, respectively. It must be noted that, in $z$-direction, system is symmetric and, the simulation region is considered as two-dimensional $(x, y)$. Thus, the anode and cathode electrodes are placed at $y = 0$ and 4 mm, and therefore, the air-gap size and solid dielectric thicknesses along $y$-direction are $D = 3$ mm and $d = 0.5$ mm, respectively.

In this work, the entire of domain including air gap and the two solid dielectrics is approximated using a lumped linear circuit. A typical transmission line based TLM method [9] is shown in Figure 2a. Moreover, RLC models can be used to consider the various aspects of energy dissipation and storage in the magnetic and electric fields in the solid insulating materials. Since the magnitude of magnetic fields producing by the currents
in the bulk of considered insulating system is insignificant, the inductance of RLC model can be ignored. Thus, in the present study, the typical RC circuit element is used, as seen in Figure 2b. Besides, the TLM method provides a complete description for the electrodynamics problems via the topological network structures. Here, the circuit model is composed of the compact lumped RC elements. Interestingly, in this circuit model, the space and time discretization along with the network concepts in electromagnetic field theory can be considered [10]. In addition, before the numerical calculations, the step-sizes can be assessed. Hence, the created errors in the discretization process will be known. Furthermore, owing to the fact that, the step-sizes are controllable, the small step-sizes are unnecessary for convergence. Thus, the produced errors with the large step-sizes are insignificant. In addition, the sensitivity inclusion to the simple linear networks is possible [11]. Besides, since the spatial length is finite, an infinite number of locations for the memory storage is unnecessary. On the other hand, to avoid the long run-time durations, a finite time sampling will be used. Therefore, in TLM method, choosing the spatial length, $\Delta x$, and temporal length, $\Delta t$, is important. Thus, the simultaneous lumping of the capacitive, resistive properties is helpful to achieve a proper spatial sampling.

![Diagram of TLM scheme](image)

**Figure 2.** (a) A cascade of segment part of transmission line [9], (b) a typical RC circuit element (capacitance $C$ and resistances $R_x$, $R_y$ and $r_y$).

A segmental part for TLM scheme is shown in Figure 3. Moreover, the physical dimensions of each infinitesimal segment in $x$- and $y$-directions are $\Delta x$ and $\Delta y$, respectively. If Kirchhoff’s current law (KCL) is applied in a typical node, the following differential equations will be obtained:

$$
\frac{\partial I_x(x, y, t)}{\partial x} \cdot \Delta x = \frac{V_y(x, y, t)}{Z(x, y, t)} - \frac{V_y(x + \Delta y, t)}{Z(x + \Delta y, t)}
$$  \(1\)

$$
\frac{\partial I_y(x, y, t)}{\partial y} \cdot \Delta y = \frac{V_x(x, y, t)}{R_x(x, y, t)} - \frac{V_x(x + \Delta x, y, t)}{R_x(x + \Delta x, y, t)}
$$  \(2\)

$$
I_y(x, y, t) = C \cdot \frac{dV_c(x, y, t)}{dt} + \frac{V_c(x, y, t)}{R_y(x, y, t)} = \frac{V_y(x, y, t) - V_c(x, y, t)}{r_y}
$$  \(3\)

Here, $Z$ denotes the formed impedance by the resistances $r_y$, $R_y$ and capacitor, $C$, as shown in Figure 3. In addition, while $V_x$ and $V_y$ show the potentials in $x$- and $y$-directions, $I_x$ and $I_y$ stand for the currents flow in these directions. To relate the voltage and current in the entire of solid insulating system, the governing equations might be written using the Kirchhoff Voltage Law (KVL) in the following forms:

$$
V_z(x, y, t) = I_x(x, y, t) \cdot R_x(x, y, t)
$$  \(4\)
\[ V_y(x, y, t) = V_c(x, y, t) + I_y(x, y, t) \cdot r_y(x, y, t). \] (5)

As shown in Figure 4, the TLM method is completely described using the RC circuit elements. Furthermore, in the proposed model, the spatial and temporal variations of charged carriers density are obtained using the continuity and Schottky’s equations. Moreover, the conductivity and Poisson’s equations are coupled with the continuity and Schottky’s equations to obtain the variations of electric potential and resistances in the solid insulating material encapsulating the gaseous void. Finally, to obtain the electron temperature distribution and their spatiotemporal behaviors within the gas medium, the kinetic energy equation is solved. Moreover, since the considered resistances for the insulation vary with the space charge and temperature, the obtained circuit equations from the TLM method are coupled with the space charge continuity and kinetic energy equations. In Figure 4, the number of RC segments is 1320. It must be noted that, while 660 segments are located in the anode and cathode barriers, the locations of 660 segments are in the gaseous medium.

Based on Figures 3 and 4, KCL equations in \((i, j)^{th}\) nodes can be discretized as follows:

\[
\begin{align*}
\left( \begin{array}{l}
C_{Ab_{i,j}} \frac{dV_{CA_{by_{i,j}}}}{dt} + \frac{V_{CA_{by_{i,j}}}}{R_{Ab_{i,j}}} = C_{Ab_{i,j}} \frac{dV_{CA_{by_{i,j+1}}}}{dt} + \frac{V_{CA_{by_{i,j+1}}}}{R_{Ab_{i,j+1}}} \\
C_{G_{i,j}} \frac{dV_{CG_{yi,j}}}{dt} + \frac{V_{CG_{yi,j}}}{R_{G_{i,j}}} = C_{G_{i,j}} \frac{dV_{CG_{yi_{i+1,j}}}}{dt} + \frac{V_{CG_{yi_{i+1,j}}}}{R_{G_{i,j+1}}}
\end{array} \right)_{i=2;N_{Ab}+1,j=1:10} \\
\left( \begin{array}{l}
C_{Cb_{i,j}} \frac{dV_{CC_{by_{i,j}}}}{dt} + \frac{V_{CC_{by_{i,j}}}}{R_{Cb_{i,j}}} = C_{Cb_{i,j}} \frac{dV_{CC_{by_{i+1,j}}}}{dt} + \frac{V_{CC_{by_{i+1,j}}}}{R_{Cb_{i,j+1}}}
\end{array} \right)_{i=2;N_{Ab}+2;N_{G}+1,j=1:10}
\end{align*}
\] (6)

where \(A_b\), \(G\) and \(C_b\) stand for parameters in the anode barrier, gas media and cathode barrier, respectively. Moreover, \(N\) denotes the number of rows of TLM matrices. Besides, applying KVL on \((i, j)^{th}\) loop will lead
Figure 4. Block diagram of charge transport in solid insulating material encapsulating a void of submillimeter dimensions.

to the following equations:

\[
\begin{align*}
V_{Ab_{i,j+1}} + V_{Ab_{x_{i,j}}} - V_{Ab_{x_{i-1,j}}} & = 0 \quad i=2:N_{Ab}+1, j=1:10 \\
V_{G_{i,j+1}} + V_{G_{x_{i,j}}} - V_{G_{x_{i-1,j}}} & = 0 \quad i=2:N_{Ab}+2, N_{G}+1, j=1:10 \\
V_{Cb_{i,j+1}} + V_{Cb_{x_{i,j}}} - V_{Cb_{x_{i-1,j}}} & = 0 \quad i=N_{Ab}+N_{G}+2, N_{Ab}+N_{G}+N_{Ca}+1, j=1:10
\end{align*}
\]
The dynamical resistors in Equation (6) are obtained through the following relations:

\[
R = \frac{\Delta x}{\sigma \cdot (\Delta y \cdot h)},
\]

where \(h\) and \(\epsilon\) are the insulator depth in \(z\)-direction and dielectric permittivity, respectively. In addition, the corresponding conductivities in gas media are defined as \(\sigma\) in the following forms:

\[
\sigma_{G,i,j} = e \cdot (n_{e,i,j} \cdot \mu_e + n_{n,i,j} \cdot \mu_n + n_{p,i,j} \cdot \mu_p),
\]

where \(e\) and \(\mu\) denote the effective mobility and elementary charge, respectively. Furthermore, \(n_e\), \(n_p\) and \(n_n\) denote the electrons, positive and negative ions in the discharge medium, respectively, which are described by the continuity and Poisson’s equations [7] and, they are discretized based on the following differentiation procedure (at \(d < y < d + D\), as seen in Figure 5):

\[
\begin{align*}
\frac{\partial n_{e,i,j}}{\partial t} &|_{i=1+N_{Ab}+1+1+N_{Ab}+N_G} = \mu_e \cdot \left( \frac{V_{G,i,j}}{\Delta x} \cdot \frac{n_{e,i,j+1} - n_{e,i,j}}{\Delta x} + \frac{V_{G,y,i,j}}{\Delta y} \cdot \frac{n_{e,i,j+1} - n_{e,i,j}}{\Delta y} \right) \\
&+ e \cdot \mu_e \cdot n_{e,i,j} \cdot (n_{p,i,j} - n_{e,i,j} - n_{n,i,j}) + D_e \left( \frac{n_{e,i,j+2} - 2n_{e,i,j+1} + n_{e,i,j}}{\Delta x^2} + \frac{n_{e,i,j+2} - 2n_{e,i,j+1} + n_{e,i,j}}{\Delta y^2} \right) \\
&+ (\alpha \cdot \xi - \eta) \cdot \mu_e \cdot n_{e,i,j} \cdot \left( \sqrt{\left( \frac{V_{G,i,j}}{\Delta x} \right)^2 + \left( \frac{V_{G,y,i,j}}{\Delta y} \right)^2} \right) - \beta_{ep} \cdot n_{e,i,j} \cdot n_{p,i,j} + S_{ph} \\

\frac{\partial n_{p,i,j}}{\partial t} &|_{i=1+N_{Ab}+1+1+N_{Ab}+N_G} = \mu_p \cdot \left( \frac{V_{G,i,j}}{\Delta x} \cdot \frac{n_{p,i,j+1} - n_{p,i,j}}{\Delta x} + \frac{V_{G,y,i,j}}{\Delta y} \cdot \frac{n_{p,i,j+1} - n_{p,i,j}}{\Delta y} \right) \\
&+ e \cdot \mu_p \cdot n_{p,i,j} \cdot (n_{e,i,j} - n_{e,i,j} - n_{n,i,j}) + D_p \left( \frac{n_{p,i,j+2} - 2n_{p,i,j+1} + n_{p,i,j}}{\Delta x^2} + \frac{n_{p,i,j+2} - 2n_{p,i,j+1} + n_{p,i,j}}{\Delta y^2} \right) \\
&+ (\alpha \cdot \xi - \eta) \cdot \mu_e \cdot n_{e,i,j} \cdot \left( \sqrt{\left( \frac{V_{G,i,j}}{\Delta x} \right)^2 + \left( \frac{V_{G,y,i,j}}{\Delta y} \right)^2} \right) - \beta_{ep} \cdot n_{e,i,j} \cdot n_{p,i,j} - \beta_{pn} \cdot n_{p,i,j} \cdot n_{n,i,j} + S_{ph} \\

\frac{\partial n_{n,i,j}}{\partial t} &|_{i=1+N_{Ab}+1+1+N_{Ab}+N_G} = \mu_n \cdot \left( \frac{V_{G,i,j}}{\Delta x} \cdot \frac{n_{n,i,j+1} - n_{n,i,j}}{\Delta x} + \frac{V_{G,y,i,j}}{\Delta y} \cdot \frac{n_{n,i,j+1} - n_{n,i,j}}{\Delta y} \right) \\
&+ e \cdot \mu_n \cdot n_{n,i,j} \cdot (n_{p,i,j} - n_{e,i,j} - n_{n,i,j}) + D_n \left( \frac{n_{n,i,j+2} - 2n_{n,i,j+1} + n_{n,i,j}}{\Delta x^2} + \frac{n_{n,i,j+2} - 2n_{n,i,j+1} + n_{n,i,j}}{\Delta y^2} \right) \\
&+ \eta \cdot \mu_e \cdot n_{e,i,j} \cdot \left( \sqrt{\left( \frac{V_{G,i,j}}{\Delta x} \right)^2 + \left( \frac{V_{G,y,i,j}}{\Delta y} \right)^2} \right) - \beta_{pn} \cdot n_{p,i,j} \cdot n_{n,i,j}.
\end{align*}
\]

Here, \(\alpha\) and \(\mu\) are the coefficients for the ionization and attachment, respectively; \(\xi\) represents a backward diffusion owing to the steep gradients in the density of electrons [12]; \(\beta_{ep}\) and \(\beta_{pn}\) are the electrons-positive ions and positive-negative ions coefficients, respectively [13]. Finally, the term \(S_{ph}\) is the photoionization rate [14]. Moreover, to obtain the electrons temperature in gaseous discharge medium in the void of submillimeter dimensions, the equation describing the electrons kinetics energy in the plasma discharges [15] can be discretized.
as follows:

\[
\begin{align*}
\frac{\partial n_{i,j}}{\partial t} & \left|_{i=1+N_{Ab}+1} \right. = -R_{ch} n_{ei,j} - R_{ch} n_{ht,i,j} - T_e n_{ei,j} \left(1 - \frac{n_{et,i,j}}{n_{et}}\right) + v \cdot n_{et,i,j} \cdot \exp\left(\frac{\varphi_{0,i,j}}{kT}\right) \cdot \frac{n_{et,i,j}}{n_{et}} \\
\frac{\partial n_{h,i,j}}{\partial t} & \left|_{i=1+N_{Ab}} \right. = \mu_h \cdot \left(\frac{V_{Ah,i,j}}{\Delta x}\right) \cdot \left(\frac{n_{h,i+1,j}-n_{h,i,j}}{\Delta x}\right) + \left(\frac{V_{Ah,y,i,j}}{\Delta y}\right) \cdot \left(\frac{n_{h,i+1,j}-n_{h,i,j}}{\Delta y}\right) \\
\frac{\partial n_{et,i,j}}{\partial t} & \left|_{i=1+N_{Ab}} \right. = -R_{ch} n_{et,i,j} - R_{ch} n_{ht,i,j} + T_e n_{et,i,j} \left(1 - \frac{n_{et,i,j}}{n_{et}}\right) + v \cdot n_{et,i,j} \cdot \exp\left(\frac{\varphi_{0,i,j}}{kT}\right) \cdot \frac{n_{et,i,j}}{n_{et}} \\
\frac{\partial n_{ht,i,j}}{\partial t} & \left|_{i=1+N_{Ab}} \right. = -R_{ch} n_{et,i,j} - R_{ch} n_{ht,i,j} + T_h n_{ht,i,j} \left(1 - \frac{n_{ht,i,j}}{n_{ht}}\right) + v \cdot n_{ht,i,j} \cdot \exp\left(\frac{\varphi_{0,i,j}}{kT}\right) \cdot \frac{n_{ht,i,j}}{n_{ht}} \\
\end{align*}
\]

where \( k \) is Boltzmann constant and, \( T_e \) is electron temperature in Kelvin.

In this work, the coefficients in Equations (10) and (11) are taken from [7] and [15]. Furthermore, the continuity equations including the dynamics of the density of charged carriers in solid dielectric can be discretized as follows (at \( 0 < y < d \), as seen in Figure 5):

\[
\begin{align*}
\frac{\partial n_{i,j}}{\partial t} & \left|_{i=1+N_{Ab}+1} \right. = \mu_e \cdot \left(\frac{V_{Ah,i,j}}{\Delta x}\right) \cdot \left(\frac{n_{i+1,j}-n_{i,j}}{\Delta x}\right) + \left(\frac{V_{Ah,y,i,j}}{\Delta y}\right) \cdot \left(\frac{n_{i+1,j}-n_{i,j}}{\Delta y}\right) \\
+ & \mu_e \cdot n_{ei,j} \cdot \left(\frac{n_{h,i,j}}{n_{ei,j}} \right) + n_{ht,i,j} - n_{et,i,j} + D_e \cdot \left[\frac{n_{i+1,j}-n_{i,j}}{(\Delta x)^2}\right] + \left(\frac{n_{i+1,j}-n_{i,j}}{(\Delta y)^2}\right) \\
+ & -R_{cht} n_{ei,j} - R_{cht} n_{ht,i,j} - T_e n_{ei,j} \left(1 - \frac{n_{et,i,j}}{n_{et}}\right) + v \cdot n_{et,i,j} \cdot \exp\left(\frac{\varphi_{0,i,j}}{kT}\right) \cdot \frac{n_{et,i,j}}{n_{et}} \\
\frac{\partial n_{h,i,j}}{\partial t} & \left|_{i=1+N_{Ab}} \right. = \mu_h \cdot \left(\frac{V_{Ah,i,j}}{\Delta x}\right) \cdot \left(\frac{n_{h,i+1,j}-n_{h,i,j}}{\Delta x}\right) + \left(\frac{V_{Ah,y,i,j}}{\Delta y}\right) \cdot \left(\frac{n_{h,i+1,j}-n_{h,i,j}}{\Delta y}\right) \\
+ & \mu_h \cdot n_{h,i,j} \cdot \left(\frac{n_{h,i,j}}{n_{ei,j}} \right) + n_{ht,i,j} - n_{et,i,j} + D_h \cdot \left[\frac{n_{h,i+1,j}-n_{h,i,j}}{(\Delta x)^2}\right] + \left(\frac{n_{h,i+1,j}-n_{h,i,j}}{(\Delta y)^2}\right) \\
+ & -R_{cht} n_{h,i,j} \cdot n_{et,i,j} - R_{cht} n_{h,i,j} \cdot n_{et,i,j} - T_h n_{h,i,j} \left(1 - \frac{n_{ht,i,j}}{n_{ht}}\right) + v \cdot n_{ht,i,j} \cdot \exp\left(\frac{\varphi_{0,i,j}}{kT}\right) \cdot \frac{n_{ht,i,j}}{n_{ht}} \\
\end{align*}
\]

In Equation (12), \( n_e, n_h, n_{et} \) and \( n_{ht} \) are densities of electrons, holes, trapped electrons and trapped holes in the bulk of solid insulating barrier on the anode, respectively. Moreover, \( R_{cht}, R_{cht}, R_e \) and \( R_{cht} \) are the
recombination coefficients of mobile electrons-trapped holes, trapped electrons-mobile holes, mobile electrons-holes and trapped electrons-trapped holes, respectively. Besides, $T_e$ and $T_h$ are the trapping coefficients for electrons and holes, respectively. Here, $\nu$ stands for the attempt to escape frequency and, $\varphi_{etr}$ and $\varphi_{htr}$ are barrier heights for detrapping of electrons and holes. In addition, $D_e$ and $D_h$ denote diffusion coefficients of electrons and holes, respectively; $\mu_e$ and $\mu_h$ are the effective mobilities of electron and holes, respectively.

Besides, $\theta$ is temperature in Kelvin and, $k$ is Boltzmann constant. The equations for the dielectric barrier on the cathode sides are similar to the above equations. However, the mobile and trapped holes densities are insignificant.

In this work, Equations (10) to (12) are solved simultaneously to describe the spatial and temporal evolution of technical parameters along with the charge transfer in both the gaseous discharge medium (void) and solid insulating layers. Besides, the injection of charged particles from the metallic electrodes into the bulk of solid insulating material and their spatiotemporal behaviors in the positions close to the metallic electrodes are already given by Serdyuk et al. [7]. Furthermore, the equations for boundary conditions on the gaseous void-dielectric barrier interface in the cathode-side can be extracted by Maxwell’s equations. Thus, the discontinuity law for the vertical component of electric field (in $y$-direction) can be rewritten as follows:

$$
\epsilon_{\text{solid}} \frac{VCG_{y_{i,j}}}{\Delta y} \bigg|_{i=1+N_{Ab}+N_G+1} - \epsilon_G \frac{V_{y_{i,j}}}{\Delta y} \bigg|_{i=1+N_{Ab}+N_G} = -e \cdot n_{e_{i,j}} \bigg|_{i=1+N_{Ab}+N_G+1},
$$

(13)

where $n_e$ denotes the extracted electrons density from the cathode-side barrier that are injected into gaseous medium (at $y = d + D$, as seen in Figure 5) due to the field emission [7]. Thus, it can be expressed as follows:

$$
n_{e_{i,j}} \bigg|_{i=1+N_{Ab}+N_G+1} = \frac{A \cdot T^2}{e \cdot \mu_e} \cdot \exp\left(-\frac{e \cdot \varphi_e}{k \cdot \theta}\right) \cdot \frac{\exp\left(\frac{e \cdot \varphi_e}{k \cdot \theta}\right)}{\sqrt{\left(\frac{VCG_{y_{i,j}}}{\Delta y}\right)^2 + \left(\frac{V_{y_{i,j}}}{\Delta y}\right)^2}}
$$

(14)

Where, $\theta$, $k$ and $A$ are the temperature in Kelvin, the Boltzmann constant and the Richardson’s constant [7]. Furthermore, $\varphi_e$ expresses the barrier height for electron extraction from the cathode-side dielectric layer.

Equation (13) can be rewritten for the boundary between the gaseous medium and the anode-side barrier as follows:

$$
\epsilon_G \cdot \frac{V_{Gy_{i,j}}}{\Delta y} \bigg|_{i=1+N_{Ab}+1} - \epsilon_{\text{solid}} \cdot \frac{V_{AGy_{i,j}}}{\Delta y} \bigg|_{i=1+N_{Ab}} = -e \cdot n_{e_{i,j}} \bigg|_{i=1+N_{Ab}},
$$

(15)

where

$$
n_{e_{i,j}} \bigg|_{i=1+N_{Ab} (y = d)} = n_e (d < y < d + D) \bigg|_{i=1+N_{Ab}+1},
$$

(16)

where $n_e$ is the electron density injected from gas medium to anode barrier (at $y = d$, as seen in Figure 5). A finite number of electrons (about $10^5 \text{ cm}^{-3}$) is assumed to be the exist initially in the gaseous void. Moreover, at the time moment of $t = 0$, the high voltage is applied as a step function, i.e. $V_a - V_e$. Since in the gaseous discharge medium, the positive and negative ions coexist, their densities are negligible in the bulk of anode and cathode dielectric layers and their surfaces. Moreover, in both media, the charged particles reaching the barrier surfaces with the opposite potential biases will be neutralized. Moreover, the density of injected holes from the
anode-sides dielectric barrier is given as follows (at $y = 0$, as seen in Figure 5):

$$n_h |_{i=1} (y = 0) = \frac{AT^2}{e \mu_h} \exp\left(-\frac{e \varphi_a}{k \theta}\right) \exp\left(\frac{e}{k \theta} \sqrt{\frac{V_{Ax(i,j)}}{\Delta x^2} + \frac{V_{Ay(i,j)}}{\Delta y^2}}\right)$$

(17)

where $\varphi_a$ expresses the barrier height for injection of holes from anode-sides dielectric barrier. However, owing to the existence of internal boundaries, the electronic components will be required for the special considerations. Hence, the injection electrons from the cathode electrode will take place in the following form (at $y = 2d + D$, as seen in Figure 5):

$$n_e |_{i=1+N_{Al}+N_{G}+N_{Ch}+1} (y = 4 \text{mm}) = \frac{AT^2}{e \mu_e} \exp\left(-\frac{e \varphi_c}{k \theta}\right) \exp\left(\frac{e}{k \theta} \sqrt{\frac{V_{Cx(i,j)}}{\Delta x^2} + \frac{V_{Cy(i,j)}}{\Delta y^2}}\right)$$

(18)

where $\varphi_c$ denotes the barrier height for the electron injection from cathode electrode.

**Figure 5.** Block diagram of charges density in solid insulating material encapsulating a void of submillimeter dimensions.

In this work, since the main objective is to examine the spatiotemporal behaviors of the various physical and technical parameters of the charge transport in the gaseous medium under HVDC application, the ordinary differential equations (10) to (12) must be solved simultaneously. The constant parameters in these equations
are presented in [7]. Hence, these equations are solved using 4th order Runge-Kutta numerical method in MATLAB software environment.

In the developed code, the time-steps are chosen through an automatic procedure. Moreover, the simulation precision is increased based on using \((132 \times 10)\) RC segments. Thus, 6900 coupled ODE’s along with boundary conditions are solved simultaneously. Besides, the computational error was less than \(6.4352463 \times 10^{-53}\). Besides, the performed numerical calculations are significantly affected by the element sizes \((\Delta x, \Delta y)\) and time-step \((\Delta t)\). For the quite large time-steps, the higher time duration for the transport of charged carriers compared with the carrier mobility will make the explicit difference scheme instable. On the other hand, for the small time-steps, the total required time to perform the calculations will increase drastically. Thus, as shown in Figure 6, for the element \(ijm\), \(\Delta t \leq d/V_i(t)\), where \(V_i(t)\) is the charged particles velocity at the nodal point ‘\(i\)’. In addition, ‘\(d\)’ is the minimum space projection between the node ‘\(i\)’ and the other two adjacent nodes in the direction of \(V_i(t)\) [16].

![Figure 6. An example for the time step limitation [16].](image)

3. Results

Generally, the presence of space charges inside the insulating materials will reflect in the distortion of externally applied electric field. These space charges might be created, trapped or injected into the bulk of solid insulating material from the metallic electrodes or voids of submillimeter dimensions encapsulating within their structures.

Based on the application of \(V_{app} = 10 kV\) on the metallic electrodes at the room temperature, an electric field of about \(E \approx 54 kV/cm\) will be appeared across the gaseous void at the initial time moment, i.e. \(t = 0\). The spatiotemporal profile for the electric field in both the dielectric barrier and void media at \(t = 0\) is shown in Figure 7a. Since there is no space charge in the bulk of insulation at this time moment, the electric field is distributed at the boundary of two insulators and, it is inversely proportional to the dielectric constant. From the time moment of \(t = 0\) onwards, the unipolar charging of dielectric layers on the anode and cathode sides will occur in the process of charges injection from the metallic electrodes, according to Equation (12), and gaseous discharge in the void. Besides, Figure 7b shows the spatial and temporal profile of electric field before reaching the spark discharge to the interface of cathode dielectric barrier and gaseous medium. As shown, the electric
field increases negatively towards the anode electrode in the gaseous medium. Owing to the higher formation rate of charged particles, the electric field across the insulating material varies significantly. Besides, at the metallic electrodes proximity, owing to the larger ionization rate of traps, the electric field varies with a higher rate and, it is under influences of space charges along with the injection of charged carrier from the electrodes.

![Figure 7](image_url)

**Figure 7.** (a) Electric field distribution at the time moment of $t = 0$ and, (b) the spatiotemporal variations of electric field distribution in the entire of solid insulating system before the appearance of initial electrons in the void.

In Figure 8, the temporal evolutions of charged particles, electric current, potential and electrons temperature after appearance of the initial electrons in the void are shown. The presented results in Figure 8 are obtained via solving the continuity and Poisson’s equations, which are simultaneously coupled with the KVL and KCL equations. The electrons are initially injected into the gaseous medium from the cathode dielectric layer and move under the high electric field influences across the gaseous void. These electrons experience the maximum electric field in the anode barrier proximity. Moreover, these electrons ionize the gas (air) atoms and molecules during their movement from the cathode to anode barriers; hence, a plenty of electrons, positive and negative ions will be formed in the gaseous medium. In the performed simulations, it is assumed that, the appearance of initial electrons is occurred at $t = 1000\, s$ on the interface of cathode barrier and gaseous medium. As seen in Figure 8a, the electrons density peaks at about $t = 1000\, s$ after the high voltage application with a width of $2\, \mu s$. Moreover, the expansion of this peak at around the time moment of $t = 1000\, s$ is shown in Figure 8b. As seen, this peak itself includes five peaks with much lower widths. In addition, the negative ions, positive ions and net charge densities have similar temporal variations, as seen in Figures 8c–8e. Besides, as shown in Figure 8e, at $t = 1000\, s + 920\, ns$, the net charge density is about $8\, nC/cm^3$. At the same time moment, Figures 8b–8d show that the electron, negative and positive ion densities are $3.5\times10^{10}\, cm^{-3}$, $5.5\times10^{10}\, cm^{-3}$ and $9.3\times10^{10}\, cm^{-3}$, respectively. On the other hand, the total transferred charges in a single pulse are $3\, nC/cm^3$. 
and $8 \, nC/cm^3$ which are carried by the predischarge (avalanche) and main discharge (streamer) pulses, respectively. Hence, memory charges and stored energy are absent in the interpulse intervals for the electrons and positive ions. It means that, after each discharge pulse, the electrons and positive ions density will be almost disappeared. It must be noted that, for the negative ions and net charge densities, in a direct process, the external circuit deposit enough energy to the primary discharge. Moreover, the stored energy via the memory charges will provide enough energy for the secondary discharge [17].

The temporal variations of discharge current as a helpful tool to describe both the avalanche and streamer processes are presented in Figure 8f. To calculate the discharge electric current, the following relations are used:

$$\begin{align*}
E &= -\nabla V \\
J &= \sigma \cdot E \\
I &= J \cdot A,
\end{align*}$$

(19)

where $J$ and $A$ are the current density and the surface area of the solid insulation, respectively.

The first impulse is related to the charging current which is owing to the capacitive properties of system and, hence, it is not a PD pulse. As shown, the first PD pulse is occurred with a short time delay after the high voltage application. The stochastic variations of the peaks magnitudes of PD pulses are, however, expected. In addition, the discharge current between the two consecutive pulses is small. This weak current is known as “residual current peak”. Here, it is about $50 \, mA$ after the primary discharge current pulse. This indicates that, the number of initial electrons in the microcavity are enough to initiate the discharge pulse at even the lower applied electric fields [18]. To perform more clarifications on different phases of discharge evolution, the magnified time variations of discharge current are shown in Figure 8g. As seen, while the amplitude of the predischarge pulse (avalanche pulse) is about $10 \, mA$, the main pulse (streamer pulse) reaches at about $550 \, mA$.

Thus, the formation and propagation of avalanche pulses are very slow and insignificant. On the other hand, the charges relaxation is followed by the avalanche pulse towards the anode barrier and streamer formation. They both take the time duration of about $50 \, ns$ which is associated with a slow current increment. Moreover, due to the intensive charges generation and their quickly lost in the streamer propagation, the current magnitude will be enhanced. Furthermore, the arrival of streamer to the cathode dielectric barrier is followed by the charge relaxation. This reflects in the current magnitude reduction. However, owing to the barrier surface and external conditions, this process takes a quite long time. During this phase of discharge propagation, various mechanisms such as surface recombination, charges neutralization, trapping process in surface traps, the ions reactions on the barriers surface and etc. are involved. These results cooperate the numerical and experimental findings Serdyuk et al. [7], Kupershtokh et al. [19] and Kang et al. [20]. Furthermore, the temporal variations of the discharge current pulse i.e. different phases of discharge evolution including the formation of electron avalanche and streamer emission finding by Serdyuk et al. [7], are shown in Figure 8h. As seen in Figures 8g and 8h, the time interval between the stages of electron avalanche formation and the relaxation of charges in the cathode barrier is higher than that of the finding by Serdyuk et al. [7]. On the other hand, the magnitude of the discharge current owing to the streamer emission and the residual discharge current causing by the surface charges relaxed in the cathode barrier are higher than that of the obtained results by Serdyuk et al. [7].

It must be noted that, the discharge ignition and extinction in the voids of submillimeter dimensions encapsulated in the solid insulating materials are under the control of its electrical potential. The electric potential across the void must be enough for the discharge initiation. The ignition applied voltages for the primary and secondary discharges are shown in Figure 8i as $3.5 \, kV$ and $2.4 \, kV$, respectively. The discharge
voltage is obtained through solving the KVL and KCL equations \((6)\) and \((7)\) which are simultaneously coupled with the continuity equations \((10)\) and \((12)\). As shown, these are much smaller than the breakdown voltage (Paschen’s curve). Moreover, the corresponding voltages to distinguish the discharge for the primary and secondary discharges are about \(1.6\) and \(1.8\,kV\), respectively. A strong reduction in the discharge voltage after the primary discharge is observable. Furthermore, Figures \(8f\) and \(8i\) show that, the time duration for the runaway current pulse is mostly equal to the time duration for the voltage trailing edge. This is confirmed by presented results by Kozyrev et al. \[21\].

In addition, Equation \((11)\) is solved to obtain the temporal variations of electrons temperature, as shown in Figure \(8j\). As seen, at applied voltage of \(10\,kV\) and during the primary discharge, the maximum electron temperature is about \(0.06\,eV\) which is occurred at about \(20\,ns\) after its corresponding discharge pulse. It must be noted that, after the dissociative recombination of electrons, the electron temperature is rapidly decreased in a time duration of \(28\,ns\), after the primary current peak is distinguished. These results are in agreement with the findings of Roettgen et al. \[22\]. Furthermore, the temporal decay of electrons temperature occurs from \(kT_e \sim 0.03\,eV\) to \(kT_e \sim 0.001\,eV\) in a time duration of about \(3\,ns\) which is much quicker than the electrons density. This is, however, owing to the fact that, the electrons energy is lost in their collisions with the air atoms. This energy dissipation occurs on the time scales that are much shorter than the time durations corresponding to the two and three body charged particles recombination phenomena. These results are in agreement with the findings of Roettgen et al. \[22\], Lin et al. \[23\] and Xinghua et al. \[24\].

As already discussed, using the TLM method, the charged carrier density and the electron temperature are obtained in the entire of the solid insulation via solving the continuity equations \((10)\), \((12)\) and the kinetic energy equation \((11)\). Figures \(9a–9g\) show the spatial distribution of charged carrier density and the electron temperature at different time moments. As seen in Figures \(9b\) and \(9c\), the electrons density in the gaseous medium increases as a result of their injection from the cathode dielectric barrier. In fact, these electrons are extracted from the cathode barrier under the influences of the strong electric field on the cathode barrier and gaseous medium interface. However, as shown in Figure \(9b\), these electrons ionize the gas atoms and molecules. Since the resultant electric field in the regions closer to the cathode dielectric is maximized, much number of charged particles are formed in these ionization regions. Moreover, upon the arrival of electrons to the anode barrier proximity, the electrons in the avalanche head will penetrate into the bulk of anode dielectric barrier, as seen in Figure \(9a\). Moreover, at the anode barrier region, their speed is reduced drastically. This is owing to a complete change in their interaction mechanisms with the void boundaries. These drastic changes will reflect in the electronic charge accumulation on both sides of the interface of gaseous medium and anode barrier, as shown in Figure \(9a\). Moreover, the drastic reduction of electrons density in the anode barrier is confirmed by the numerical findings by Serdyuk et al. \[7\]. Furthermore, the formed negative and positive ions in the ionization, attachment, recombination and photoionization processes in the gaseous void are depicted in Figures \(9d\) and \(9e\). In addition, since the ions mobility is much less than the electrons, their movements towards the electrodes with the opposite polarities are much slower. Besides, as depicted in Figure \(9f\) for the absolute value of net charge density in the gas medium, it is mostly governed by electrons \[7\]. Additionally, the average speed of the electrons avalanche is computed as \(0.9\times 10^7\,cm/s\), which approximately collaborates the findings by Serdyuk et al. \[7\]. Finally, Figure \(9g\) indicates the electrons temperature (kinetic energy) distributions at different time moments in the gaseous void medium. As seen, it is completely under the influences of the total electric field in void. The maximum value of electrons temperature at about the time moment of \(t = 1000\,s\) reaches \(0.14\,eV\). This cooperates the findings by Sigmond’s result \[24\].
Figure 8. (a) The electron density, (b) magnified electron density pulse, (c) negative ion density, (d) positive ion density, (e) space charge density, (f) discharge current, (g) magnified discharge current pulse (phases of discharge evolution) in present work, (h) magnified discharge current pulse (phases of discharge evolution) in Serdyuk et al. [7], (i) discharge voltage, and (j) electron temperature simulated at the gaseous media (at the position of 3.48 mm from the anode electrode).

In this work, using the TLM method, the electric field and potential in the solid insulation are obtained via solving the KVL and KCL equations. Furthermore, at the gas-solid interface, the electric field and potential are obtained using the discontinuity law for the vertical component of electric field based on Equations (13) and (15). In addition, Figures 10a and 10b show the spatial distribution of electric field and potential at different time moments. As seen in Figure 10a, before the discharge initiation in the void of submillimeter dimensions (solid curve), at the vicinity of cathode barrier and the positions higher than 3.5 mm from the metallic anode electrode (y > 3.5 mm), the potential distribution has an upward concave direction, i.e. for $\frac{\partial^2 V}{\partial y^2} > 0$ and $\rho < 0$, the electrons injection happens from the cathode side. Moreover, at the anode barrier and the distances below 0.5 mm from the metallic anode electrode (y < 0.5 mm), a downward concave direction is observable.
Besides, in the case of $\partial^2 V / \partial y^2 < 0$ and $\rho > 0$, it can be concluded that, the positive charged carriers (holes) can be injected from the anode into the bulk of the anode dielectric barrier. As shown in Figure 10a, during the electron avalanche formation in the void from $y = 0.5\,mm$ to $y = 3.5\,mm$, the concave direction is upward (blue dash-dotted curve). In the case of $\partial^2 V / \partial y^2 > 0$ and $\rho < 0$, the electron avalanche formation in this region is confirmed. Besides, as depicted in Figure 10a (red dashed curve), during the propagation of electron avalanche in the gaseous medium, while the external voltage is mostly appeared across in the anode dielectric barrier (approximately at $7.8\,kV$), the discharge voltage will fall down. These are in agreement with the findings of Serdyuk et al. [7] and Ghasemi et al. [4].

It must be noted that, on the electrons arrival from the gaseous void to the anode dielectric barrier, a streamer will start to propagate. It reflects in the higher electric fields in the streamer head, as seen in Figure 10b. On the other hands, in Figure 10a (blue dash-dotted curve), two local maximum points (in the negative direction) are visible at the positions below $0.7\,mm$ from the anode. While the larger peak corresponds to the motion of the electrons avalanche in the gaseous medium, the smaller peak corresponds to the holes and electrons injection from the metallic anode and gaseous void to the anode dielectric barrier, respectively. Furthermore, at the positions above $3\,mm$ from the anode electrode, as shown in Figure 10b, the electric field is maximized in the positive direction (blue dash-dotted and red dashed curves). These findings validate the numerical results by Serdyuk et al. [7].

In following, the influences of the gaseous void thickness and its location with respect to the metallic electrodes in the solid insulating material on the PD current are studied. As shown in Figure 11, the discharge current at different cavity thicknesses and locations is computed based on Equation (19). As seen in Figure 11a, PD pulse current is significantly influenced by the void thickness. At the higher void thicknesses, the amplitude of the discharge current increases. For instance, for the cavity thicknesses of $1.2\,mm$ and $2.2\,mm$, the peak amplitudes of the first PD pulse are $50\,mA$ and $430\,mA$, respectively. It must be noted that, while the higher cavity axial lengths (parallel to the electric field) are reflected in the higher probability of initial electrons appearance, it will cause the higher ionization rates in the traveling of charged particles towards the opposite electrodes [25, 26]. Hence, at the higher cavity lengths, the growth of avalanche size will result in the larger PD pulses currents. This cooperates the findings Ahmad et al. [27, 28] and Haqjoo [29]. Moreover, this is confirmed with the performed experiments by Illias et al. [26] and Forson et al. [30]. In addition, at the smaller thicknesses, the PD pulses occur with a slightly lower time delay. It is worth mentioning that the corresponding discharge residual currents are varied from $20\,mA$ to $70\,mA$ for the thicknesses from $1.2\,mm$ to $2.2\,mm$.

The temporal variations of PD current magnitude at different void locations in the bulk of solid insulating material are shown in Figure 11b. Here, the void thickness is taken as $0.7\,mm$, and three different spatial locations in $y$-direction are considered. They are assumed to be located in the center and at the proximity of the metallic anode and cathode electrodes in the bulk of solid insulating material. As shown in Figure 11b, the PD occurrence in the voids locating in the axial positions close to the electrodes are occurred sooner than that of the gaseous voids locating in the insulator center. On the other hand, compared with the PD pulses in the voids locating in the cathode proximity, the occurrence of PD pulses in the voids locating in the anode adjacent is sooner. Furthermore, due to the higher electric fields in the bulk of solid insulating material at the positions close to electrodes, the PD pulses magnitudes are generally higher than that in the insulator center [25].
Figure 9. Electrons density at (a) anode barrier, (b) gaseous media, (c) cathode barrier, and (d) negative ion density, (e) positive ion density, (f) space charge density, and (g) electron temperature distributions at the various time moments in gaseous media.

Figure 10. (a) Electric potential and (b) electric field distributions at the various phases of discharge propagation.

Figure 11. The temporal variations of discharge current in gaseous medium at different cavity (a) thicknesses and (b) locations.
4. Conclusion
In this paper, the charge transport mechanism in a solid insulating system consisting of a dielectric material encapsulating a gaseous void was numerically studied. The obtained two-dimensional circuit equations from TLM method were coupled with the continuity equations for the fluxes of charged carriers in both dielectric and gaseous media. Moreover, these equations were coupled with Poisson’s equation to compute the electric field and potential. Using this numerical procedure, electric field computation was much easier than the other numerical schemes. Interestingly, this model was capable of studying the surface charges accumulation effects on the residual current, voltage across the cavity and the spatial distribution of electric field. In addition, these equations were coupled with the kinetic energy equation to obtain the electrons temperature, which is important in understanding of the discharge process during the PD occurrence in the gaseous void. On the other hand, the different phases of the discharge phenomenon including formation and propagation of the electron avalanches and streamers were clearly examined using the temporal variations of the discharge current pulse and the spatiotemporal distribution of the electric potential and field amplitudes. Additionally, it was found that, the electrons in the avalanche head penetrate partially into the bulk of anode barrier while their speed was reduced drastically due to their interactions with the void-dielectric interfaces. The higher electric fields were reflected in the larger number of the formed charged particles in void in the proximity of the cathode dielectric. Moreover, during the propagation of electron avalanche in the gaseous medium, the discharge voltage was fallen down while the external voltage was mostly appeared across the anode dielectric barrier. Furthermore, at higher applied voltages, while the time delay in the occurrence of first discharge current pulse was reduced, the magnitude of discharge current was increased. Besides, at the higher void thicknesses, the amplitude of the discharge current pulses was enhanced. In addition, when the cavity is close to the metallic electrodes, the magnitude of discharge current is higher, since electric field inside the cavity becomes stronger at the cavities locating in the electrodes adjacent. Finally, in the voids locating in the axial positions close to the electrodes, the PD pluses were occurred sooner than that of the voids in the insulator center. It must be noted that, in this work, the TLM method was designed when the metallic electrodes were biased with HVDC without ripple. Moreover, different electrode structures can be implemented. Furthermore, this model was developed in the Cartesian two-dimensional coordinate system and, it can be developed for the three-dimensional systems.

References


