Systems Theory: Simulation Analysis of Space Charge Generation Mechanisms in Transformer Oil under High Electric Field

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Abstract—Simulation analysis plays an important role in Systems Theory nowadays. In order to reveal the mechanism of space charge injection and generation in the process of liquid dielectric breakdown, the discharge of transformer oil between needle-plane electrodes under high electric field is studied. Based on the 2-D hydrodynamic model and Poisson equation of electric field, the system simulation model of oil discharge by different charge generation mechanism is established, based on which the inception and propagation process of discharge is simulated by COMSOL. By system simulation, the temporal and spatial distribution of the electric field intensity, space charge density, electric potential and temperature of transformer oil is obtained and deeply analyzed. The simulation results prove that the space charge generated by metal field emission and ionic disassociation are neither of the major factor for streamer formation in transformer oil, while the Zener molecular ionization and impact ionization are the major factors. Our research improves the understanding of the inception, propagation and breakdown process for discharge in transformer oil, and also the ionization mechanism in the liquid dielectric.

Keywords—systems theory, system simulation, hydrodynamic model, COMSOL, space charge

I. INTRODUCTION

SYSTEM simulation is a set of techniques that allows computers to imitate the operations of various real-world tasks or processes through simulation. Modern computers and super-computers are used to generate numeric models for the purpose of describing or displaying complex interaction among multiple variables within a system. Simulation analysis plays an important role in Systems Theory nowadays. System simulation plays an important role in science and technology research, such as physics, chemistry, electronics, etc. Many microscopic systems can only be observed and measured in a macroscopic way, but the microscopic observation can't be implemented. System simulation is currently one powerful way to achieve this. In electrical engineering, the transformer oil is widely applied in high voltage electrical equipments as excellent dielectric for insulation and cooling. The electrical insulation quality determines the whole reliability performance of such equipments. The space charge generated under high electric field has a great impact on its electric field distribution, which is one of the most important factors causing the degrading or invalidation of insulation performance. Research has been carried out for the space charge generation and transportation, and its influence on the insulation performance of liquid dielectric. Traditional method is the measurement of macroscopic quantity such as magnitude of discharge and the macroscopic quantity of electromagnetic wave, light and sound radiated in the process of discharge by experiment equipment. However, this method faces great difficulty in revealing the temporal and spatial evolution of charged particle and electric field.

In recent years, more and more researchers simulate the discharge process, the space charge produce and propagation in transformer oil by numerical simulation. In these researches, the hydrodynamic equations are established for charge carrier. The finite-element method is utilized to implement the numerical solution of the charge carriers convective-diffusion equation, and the Poisson equation of the electric field[1].Li Yuan, et. Al. study by simulation the influence of various voltage magnitude, the pulse rising edge, the interval between electrodes on the form of steamer discharge, field intensity and the space charge density distribution[2]. Wang Qi, et, al. establish the two-phase fluid model for the discharge of liquid dielectric, and study by simulation the inception and propagation of the steamer between needle-plane electrodes under nanosecond pulse[3]. Jouya Jadidian implements the simulation study on the space charge transportation and breakdown mechanism[4].

However, current research literature only considers Zener molecular ionization in space charge generation. The metal field emission, ionic disassociation, molecular ionization and electron ionization are not considered. All of these take effect in the space charge generation. In this paper, the transformer oil is studied based on 2-D fluid dynamic model. Simulation is implemented for the evolution of field intensity, space charge density and temperature distribution with various charge generation mechanism mentioned before.

The main contribution of this paper is that it proves that the space charge generated by field emission and ionic disassociation are neither of the major mechanism for streamer discharge formation in transformer oil, while the Zener molecular ionization and impact ionization are the major factors for steamer formation. Our research improves the understanding of the inception, propagation and breakdown process for discharge in transformer oil, and also the ionization mechanism in the liquid dielectric.

II. THEORETICAL FRAMEWORK

Under the electric field of high voltage, large amount of space charge will be generated, which causes the discharge and even breakdown of the dielectric. The causation of space charge includes metal field emission, ionic disassociation, Zener molecular ionization, and impact ionization.

A. *Metal Field Emission*

This mechanism is the emission of electrons from a solid or a liquid surface into another phase under a high electric field. It occurs due to electrons tunneling through a deformed potential barrier at the interface. According to Fowler-Nordheim theory, the electron current density J_e produced by electrons tunneling through a metal surface into vacuum is described as:

$$J_e = \frac{\alpha_e |\vec{E}|^2}{\phi t^2(\frac{\Delta\phi}{\phi})} \exp[-\frac{\beta_e \phi^{\frac{3}{2}}}{|\vec{E}|} \upsilon(\frac{\Delta\phi}{\phi})] \qquad (1)$$

where $\vec{E}$ is the electric field intensity on the metal surface. $\alpha_e = 1.54 \times 10^{-6} \mathrm{eV/V^2}$, $\beta_e = 6.87 \times 10^9 \mathrm{eV^{-1.5} V/m}$. ϕ is the electric field and the work function of the metal, and $\Delta\phi$ is the decrease value of the maximum height of potential barrier at the metal interface, expressed by $3.79 \times 10^4 |\vec{E}|^{0.5}$. $t^2(\Delta\phi/\phi)$ and $\upsilon(\Delta\phi/\phi)$ can be determined by related forms. Their approximate values are:

$$t^2(\frac{\Delta\phi}{\phi}) = 1.1, \ \upsilon(\frac{\Delta\phi}{\phi}) = 0.95 - (\frac{\Delta\phi}{\phi})^2 \qquad (2)$$

When field emission occurs from a metal immersed in a dielectric liquid, it is necessary to account for the difference between energy of the electron in the liquid and vacuum[5]. The work function of the metal in vacuum should be replaced by the apparent work function ϕ_{liq}, and here the value 3.9eV is used[6].

B. *Field induced Ionic Disassociation*

The research of Onsager indicates that the neutral ion-pairs will be disassociated by electric field, which causes the change of free ion density in oil. The production rate G_D of the positive/negative ion density in the disassociation process is given as:

$$G_D(|\vec{E}|) = e\left(\frac{\sigma}{e(\mu_p + \mu_n)}\right)^2 K_R \cdot F(|\vec{E}|) \qquad (3)$$

$$F(|\vec{E}|) = \frac{I_1(4\sqrt{e^3|\vec{E}| / 16\pi\xi k^2 T^2})}{2\sqrt{e^3|\vec{E}| / 16\pi\xi k^2 T^2}} \qquad (4)$$

where e is the magnitude of electron charge($1.6 \times 10^{-19} C$). σ is the conductivity of the oil($1 \times 10^{-13} S/m$). μ_n, μ_p are the migration rates of negative ions($1 \times 10^{-9} m^2 \cdot V^{-1} \cdot s^{-1}$)and positive ions($1 \times 10^{-9} m^2 \cdot V^{-1} \cdot s^{-1}$). K_R is the recombination rate of positive and negative ions in the dielectric ($1.64 \times 10^{-17} m^3 s^{-1}$). ξ is the permittivity of the oil (2.2). k is the Boltzmann constant($1.3807 \times 10^{-23} J/K$). T is the thermodynamic temperature of the dielectric. I_1 is the first modified Bessel function[7].

Besides, there is also the recombination of free ions density under the electric field, which decreases the amount of positive and negative ion. The decrease rate G_R of ion density is:

$$G_R = \frac{n_p n_n K_R}{e} \qquad (5)$$

where n_p and n_n are the density of positive and negative ions respectively. K_R is the recombination coefficients of positive and negative ions ($1.64 \times 10^{-17} m^3 s^{-1}$),

C. *Zener Molecular Ionization*

Zener molecular ionization is a direct ionization mechanism, in which the oil molecule is directly ionized to electron and positive ion. According to the Zener theory, the production rate G_I of electron/positive ion density by field-induced tunneling ionization is:

$$G_I(|\vec{E}|) = \frac{e^2 n_0 a |\vec{E}|}{h} \exp(-\frac{\pi^2 m^* a \Delta^2}{e h^2 |\vec{E}|}) \qquad (6)$$

where h is Planck' s constant ($6.62617 \times 10^{-34} J \cdot s$), a is the molecular distance($3 \times 10^{-10} m$), m^* is the free space electron mass($9.1 \times 10^{-31} Kg$), n_0 is the number density of ionizable molecules($1 \times 10^{23} / m^3$), Δ is the ionization potential of the liquid dielectric(7.5eV)[8].

D. *Impact ionization*

Impact ionization means when the electrons with enough energy hits the gas molecule or atom, their valence electron is released and positive ion appears. It is an important theory which explains the gas breakdown mechanism. In liquid dielectric, the average free path length of electron is much shorter than that in the gas discharge. The impact ionization is not easy to happen, so the probability of avalanche is relatively low,. However, in the discharge of liquid dielectric, there exists low density area caused by molecular ionization, or gas-phase streamer channel in which impact ionization may happen. Based on the Thomson impact ionization theory, the production rate of electron density by impact ionization in the gas-phase streamer channel under high field is given as follows:

$$G_{GP}(|\vec{E}|) = \alpha_i n_e \mu_{eGP} |\vec{E}| \qquad (7)$$

$$\alpha_i = A_\alpha \exp\left(-B_\alpha / |\vec{E}|\right) \tag{8}$$

where n_e is the densities of electron and μ_{eGP} is the migration rates of electron($1\times10^{-2} m^2\cdot V^{-1}\cdot s^{-1}$). α_i is the electron impact ionization coefficient. A_α and B_α are related proportion coefficients with the value 25/m and 2 × 10^7 V/m respectively[9].

III. SYSTEM SIMULATION MODEL OF DISCHARGE FOR TRANSFORMER OIL

A. *The Geometry of Needle-plane Electrodes*

According to the test method of breakdown voltage in transformer oil (IEC Std.60897), the 2-D axial symmetric model is established[10]. The discharge system of transformer oil is shown in Fig.1. 2 is the needle electrode the curvature radius of which is 40 μ m. 5 is the plane electrode and the distance between two electrodes is 1 mm. 3 and 4 are the simulation boundary. 1 is the axis of symmetry. Because the discharge is mainly concentrated near the axis 1 of the needle electrode, the numerical gradient in this region is very large. In order to ensure the accuracy and convergence of the numerical calculation, the meshed geometry of this part is extremely precise. However, the meshed geometry of other regions is relatively sparse to reduce the amount of calculation[11]. The structure of meshes used in this simulation experiment is also shown in Fig. 1.

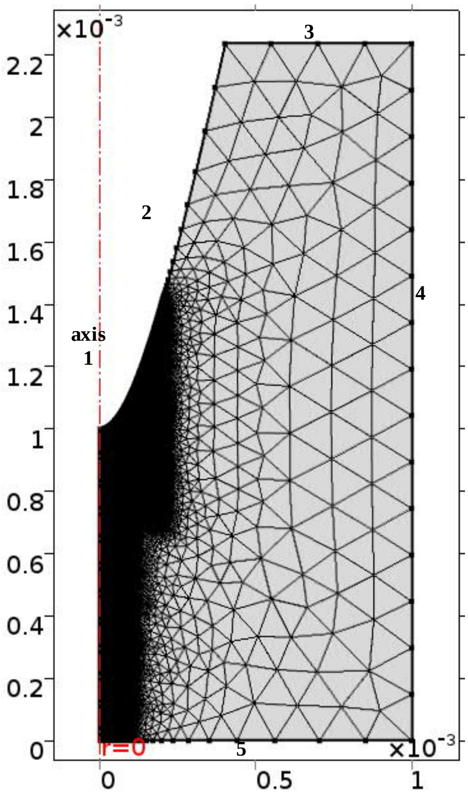


Fig.1 The structure of needle-plate electrodes and meshes

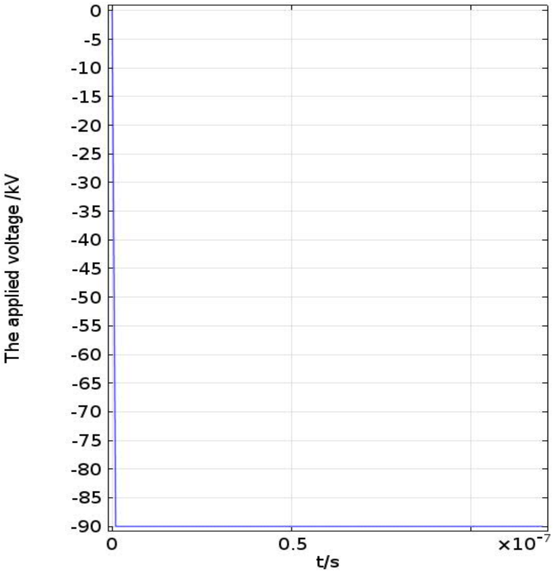


Fig.2 -90kV voltage waveform between needle-plate electrode

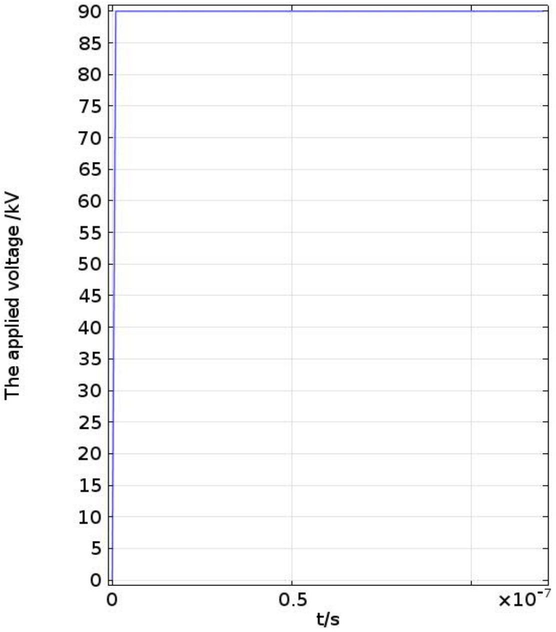


Fig.3 +90kV voltage waveform between needle-plate electrode

B. *System Simulation Model*

(1) The Simulation Model of Oil Discharge by Metal Field Emission

At the negative electrode, the electrons induced by field emission inject into the transformer oil. Some of the electrons attach to neutral species, and negative ions are formed. Therefore, two kinds of charged particles exist in this discharge process only by metal field emission. Equation (9) and equation (10) are the transportation equations of electrons and negative ions. Equation (11) is the Poisson equation of electric field and equation (12) is the heat diffusion equation, which is used to investigate the temperature rise of oil in the process of discharge. They consist of the simulation model of oil discharge by metal field emission.

$$\frac{\partial n_e}{\partial t} - \nabla \cdot n_e \mu_e \vec{E} = -\frac{n_e}{\tau_a} \tag{9}$$

$$\frac{\partial n_n}{\partial t} - \nabla \cdot n_n \mu_n \vec{E} = \frac{n_e}{\tau_a} \tag{10}$$

$$\nabla \cdot E = -\nabla^2 V = \frac{n_n + n_e}{\xi} \tag{11}$$

$$\frac{\partial T}{\partial t} + v \cdot \nabla T = \frac{1}{\rho c_v}(k_T \nabla^2 T + \vec{E} \cdot J) \tag{12}$$

where n_e, n_n are the densities of electron and negative ion. μ_e, μ_n are the migration rates of electron($1\times10^{-4} m^2 \cdot V^{-1} \cdot s^{-1}$) and negative ion($1\times10^{-9} m^2 \cdot V^{-1} \cdot s^{-1}$). T, v, ρ , c_v, k_T refers to the temperature, flow velocity(0m/s), density (880kg/m3), specific heat ($1.7 \times 10^3 J/(kg \cdot K)$), and thermal conductivity of transformer oil($0.13 W/(m \cdot K)$). J is the density of current, expressed by $J = (-n_e \mu_e - n_n \mu_n)\vec{E}$. n_e/τ_a is the rate at which electrons density are reduced by the attachment process in which τ_a is the constant of electron attachment time(2×10^{-7} S) .

(2) The Simulation Model of Oil Discharge by Ionic Disassociation

Weakly bonded neutral ion-pairs in oil are disassociated into free positive and negative ions due to the electric field, and the recombination process of free ions are also accompanied. Therefore, two kinds of charged particles exist in this discharge process only by ionic disassociation. Equation (13) and equation (14) are the transportation equations of negative and positive ions particles. $G_D(|\vec{E}|)$ and G_R are the generation and recombination rate of charged particles density by ionic disassociation which is discussed in section II.B. The simulation model of ionic disassociation is as follows:

$$\frac{\partial n_n}{\partial t} - \nabla \cdot n_n \mu_n \vec{E} = G_D(|\vec{E}|) + G_R \tag{13}$$

$$\frac{\partial n_p}{\partial t} + \nabla \cdot n_p \mu_p \vec{E} = -G_D(|\vec{E}|) - G_R \tag{14}$$

$$\nabla \cdot E = -\nabla^2 V = \frac{n_n + n_p}{\xi} \tag{15}$$

$$\frac{\partial T}{\partial t} + v \cdot \nabla T = \frac{1}{\rho c_v}(k_T \nabla^2 T + \vec{E} \cdot J) \tag{16}$$

where n_n, n_p are the densities of negative and positive ion. μ_n, μ_p are the migration rates of negative ion($1\times10^{-9} m^2 \cdot V^{-1} \cdot s^{-1}$) and positive ion($1\times10^{-9} m^2 \cdot V^{-1} \cdot s^{-1}$). In this model, J is expressed by $(n_p \mu_p - n_n \mu_n)\vec{E}$.

(3) The Simulation Model of Oil Discharge by Zener Molecular Ionization

The discharge process in liquid dielectrics is described by the convection and diffusion equations of charged particles and the Poisson equation of electric field. Equations (17), (18) and (19) are the convection and diffusion equations of charged particles, and equation (20) is Poisson equation about electric field. They are strongly coupled equations about electric field and charged particles. Equation (21) is the heat diffusion equation, [12].

$$\frac{\partial n_e}{\partial t} - \nabla \cdot n_e \mu_e \vec{E} = -G_I(|\vec{E}|) - \frac{n_e n_p R_{pe}}{e} - \frac{n_e}{\tau_a} \tag{17}$$

$$\frac{\partial n_n}{\partial t} - \nabla \cdot n_n \mu_n \vec{E} = -\frac{n_p n_n R_{pn}}{e} + \frac{n_e}{\tau_a} \tag{18}$$

$$\frac{\partial n_p}{\partial t} + \nabla \cdot n_p \mu_p \vec{E} = G_I(|\vec{E}|) + \frac{n_p n_n R_{pn}}{e} + \frac{n_p n_e R_{pe}}{e} \tag{19}$$

$$\nabla \cdot E = -\nabla^2 V = \frac{n_p + n_n + n_e}{\xi} \tag{20}$$

$$\frac{\partial T}{\partial t} + v \cdot \nabla T = \frac{1}{\rho c_v}(k_T \nabla^2 T + \vec{E} \cdot J) \tag{21}$$

where R_{pe}, R_{Pn} are the recombination coefficients of positive ions and electrons($1.64 \times 10^{-17} m^3 s^{-1}$), positive ions and negative ions($1.64 \times 10^{-17} m^3 s^{-1}$). In this mode, J is the density of current, expressed by $J = (n_p \mu_p - n_e \mu_e - n_n \mu_n)\vec{E}$. The generation rate of charged particles density by Zener molecular ionization field is expressed by $G_I(|\vec{E}|)$, which is discussed in Section II.C.

(4) The Simulation Model of Impact Ionization in the gas-phase streamer channel

The temperature of oil rises due to thermal diffusion in oil discharge. When the temperature is up to threshold, gas-phase area is identified[13].The simulation model in the gas-phase streamer channel is as follows:

$$\frac{\partial n_e}{\partial t} - \nabla \cdot n_e \mu_{eGp} \vec{E} = -G_{GP}(|\vec{E}|) \tag{22}$$

$$\frac{\partial n_n}{\partial t} - \nabla \cdot n_n \mu_{nGp} \vec{E} = 0 \tag{23}$$

$$\frac{\partial n_p}{\partial t} + \nabla \cdot n_e \mu_{pGp} \vec{E} = G_{GP}(|\vec{E}|) \tag{24}$$

$$\nabla \cdot E = -\nabla^2 V = \frac{n_p + n_n + n_e}{\xi} \tag{25}$$

$$\frac{\partial T}{\partial t} + v \cdot \nabla T = \frac{1}{\rho c_v}(k_T \nabla^2 T + \vec{E} \cdot J) \tag{26}$$

where $G_{GP}(|\vec{E}|)$ is the generation rate of charged particles by impact ionization, which is discussed in II.D. $\mu_{eGP}, \mu_{nGP}, \mu_{pGP}$ are the migration rates of electron($1\times10^{-2} m^2 \cdot V^{-1} \cdot s^{-1}$), negative ion($1\times10^{-7} m^2 \cdot V^{-1} \cdot s^{-1}$) and positive ion($1\times10^{-7} m^2 \cdot V^{-1} \cdot s^{-1}$) in the gas-phase streamer channel. J is the density of current, expressed by $J = (n_p \mu_p - n_e \mu_e - n_n \mu_n)\vec{E}$.

C. *Boundary conditions*

The interaction between particle flow and dielectric interface is very important to the discharge. When considering the boundary conditions, it is necessary to ensure the stability of calculation and the rationality of physics. As to the simulation area in Fig. 1, the boundary conditions are set as follows.

(1) Boundary conditions for Poisson equation

The symmetry axis 1 is set as r = 0. The needle electrode is set as V_0 as shown in fig.2 and fig.3, which is the hyperbolic tangent function given by equation (27). The potential of plane electrode is zero. The outer boundary 3 and 4 are set as the zero charge boundary , $n \cdot N = 0$.

$$V_0 = \pm 90 \times \tanh(1\times 10^{12} t) kV \tag{27}$$

(2) Boundary conditions for the convection and diffusion equations

The symmetry axis 1 is set as r = 0. Both the needle and plane electrodes are under convection diffusion condition $n\cdot(-D\nabla n_x)=0$. The outer boundary 3 and 4 are set as the conditions of zero charge boundary $n\cdot N=0$, $N=n_x\mu\vec{E}$.When the effect of field emission on discharge is studied, Equation (1) is the boundary condition of needle electrode.

(3) Boundary conditions for the heat diffusion equation

The symmetry axis 1 is set as r=0. The electrodes and outer boundaries are set as thermal insulation boundary $-n\cdot(-k\nabla T)=0$.

IV. SYSTEM SIMULATION RESULT AND ANALYSIS

A. *The Effect of Metal Field Emission on Transformer Oil Discharge*

To induce the metal field emission, at least $10^8 V/m$ electric field is needed near the needle. For that, -90kV pulse voltage is applied on the needle electrode. By simulation in COMSOL, he temporal and spatial evolution of electric field intensity, space charge density, and oil temperature along the symmetry axis1 are analyzed. The axis 1 is shown in Fig.1.

Fig.4 shows the distribution of electric field intensity along the axis 1 by metal field emission at 10ns, 60ns and 120ns under above discharge condition. It is shown that, the field intensity at different time reaches the maximum at the needle, and all the electric field distributions are similar with the original. This proves that, even under maximum electric field, the electron density is very low by the tunneling effect. The electric field generated by metal field emission is not sufficient to bring change to the original electric field.

Fig.5 shows the distribution of space charge density along the axis 1 by metal field emission at 0, 10ns, 60ns and 120ns under above discharge condition. This charge density is three orders lower than that in the streamer discharge described in [14]. Therefore, even the electric field is much higher than that needed to induced steamer, it cannot generate large amount of charged particles. The result proves that the metal field emission is not a main factor inducing steamer.

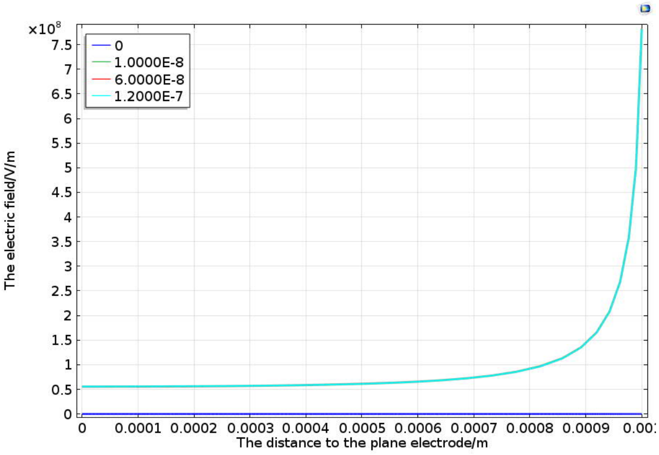


Fig.4 the distribution of electric field intensity along the axis 1 by metal field emission at 10ns, 60ns and 120ns

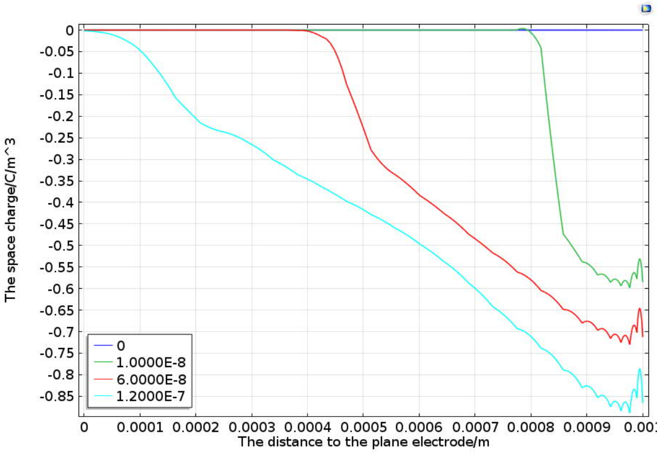


Fig.5 the distribution of space charge density along the axis 1 by metal field emission at 0, 10ns, 60ns and 120ns

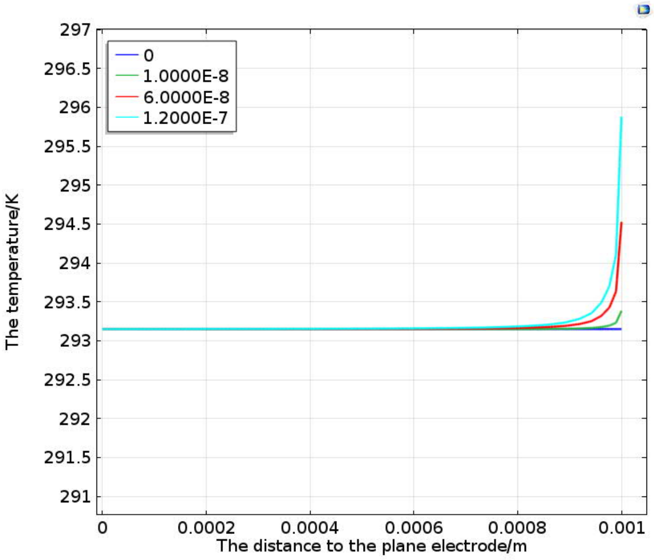


Fig.6 he distribution of temperature along the axis 1 by metal field emission at 0, 10ns, 60ns and 120ns

Fig.6 shows the distribution of temperature along the axis 1 by metal field emission at 0, 10ns, 60ns and 120ns under above discharge condition. It is shown that there is no significant temperature change. Only a few degrees rise occurs near the needle. This can also prove that field emission is not a main factor for discharge.

B. The effect of ionic disassociation on transformer oil discharge

Simulation is carried out to investigate the ionic disassociation in the inception and propagation of discharge. For that, +90kV pulse is applied on the needle electrode. The temporal and spatial evolution of electric field intensity, space charge density, and oil temperature along the symmetry axis1 are calculated only by the ionic disassociation.

Fig.7 shows the distribution of electric field along the axis 1 by ionic disassociation at 10ns, 60ns and120ns. It indicates that the peak position of field intensity is not at the pin-point all the time. It moves away from pin-point towards the plane electrodes. Free ions are generated by ionic disassociation, which generates additional electric field and changes the whole field distribution dynamically, but such field only occurs near the pin-point. The overall global distribution of the electric field is not significantly changed.

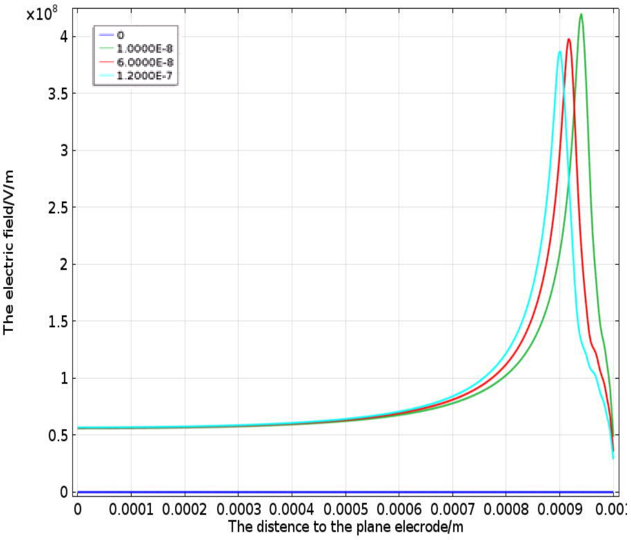


Fig.7 the distribution of electric field along the axis 1by ionic disassociation at 10ns, 60ns and120ns

The field-related ionic disassociation generates positive and negative ions. Fig. 8 shows the distribution of space charge density along the axis 1 by ionic disassociation at 0,10ns, 60ns and120ns under +90kV pulse voltage. This time-variant character exists only near the pin-point, just like the electric field discussed above.

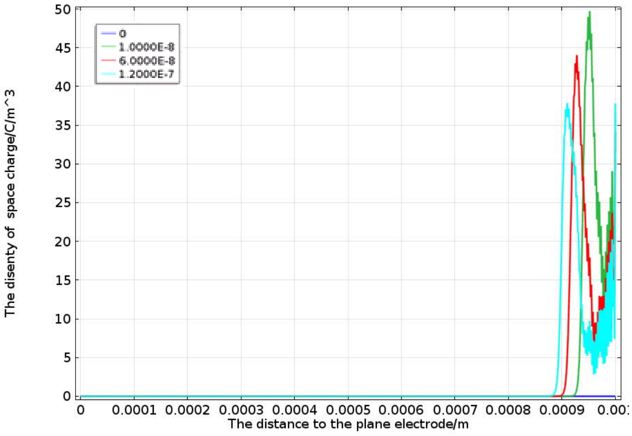


Fig.8 the distribution of space charge density along the axis 1 by ionic disassociation at 0,10ns, 60ns and120ns

Fig.9 shows the distribution of temperature along the axis 1 by ionic disassociation at 0,10ns, 60ns and 120ns. It shows that, except the small temperature increase near the needle electrode, there is no obvious global change. It proves that ionic disassociation is not a main factor for steamer discharge.

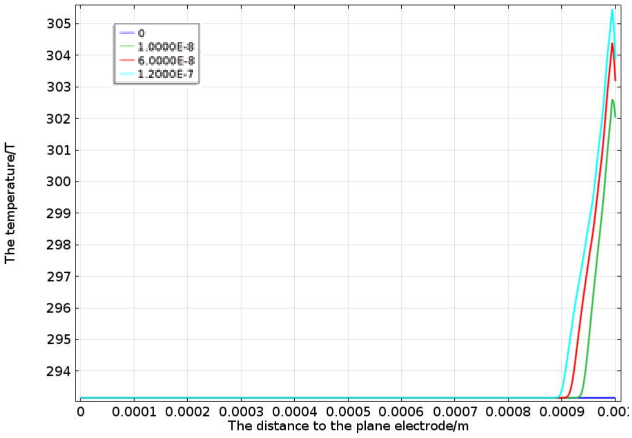
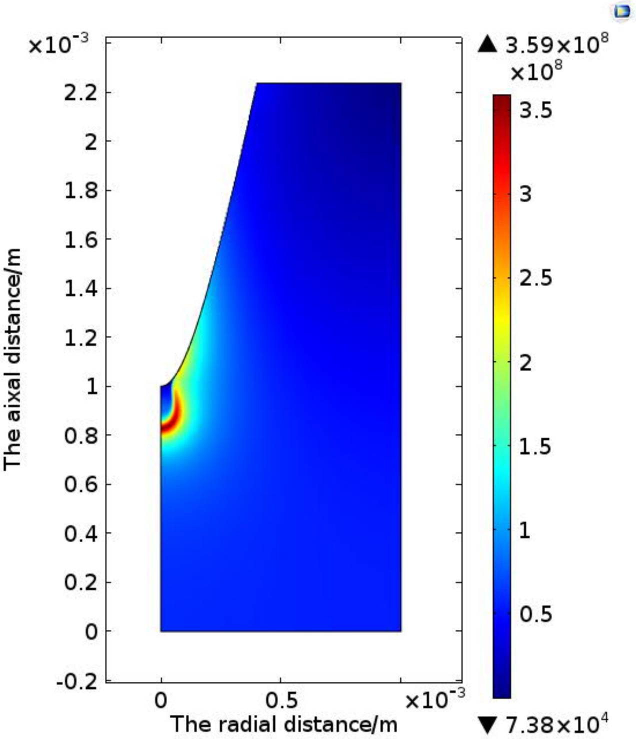


Fig.9 the distribution of temperature along the axis 1 by ionic disassociation at 0,10ns, 60ns and 120ns

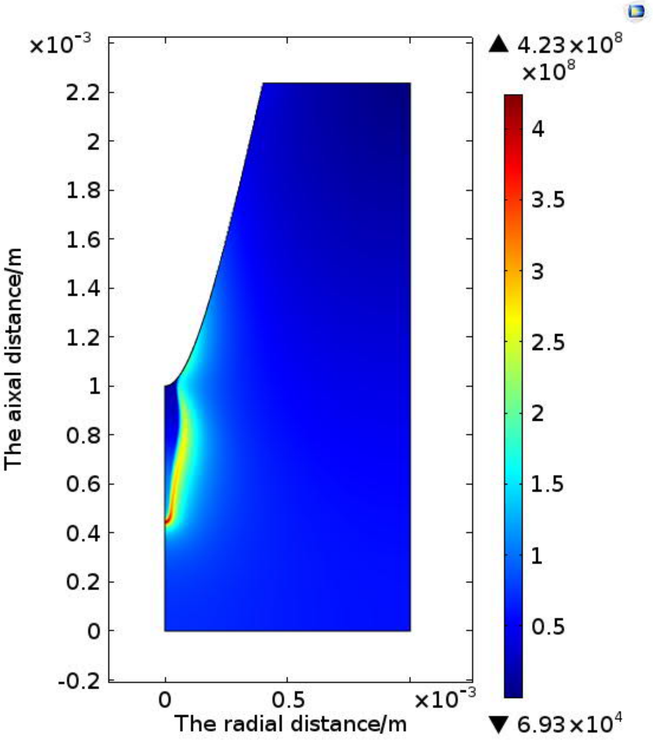
C. The effect of Zener molecular ionization on transformer oil discharge

The Zener molecular ionization is studied in the inception and propagation of discharge in transformer oil. The pulse voltage of +90kV is applied on the needle-plane electrode. The temporal and spatial evolution of electric field intensity, space charge density, and oil temperature along the axis1 are analyzed by simulation only for Zener molecular ionization.

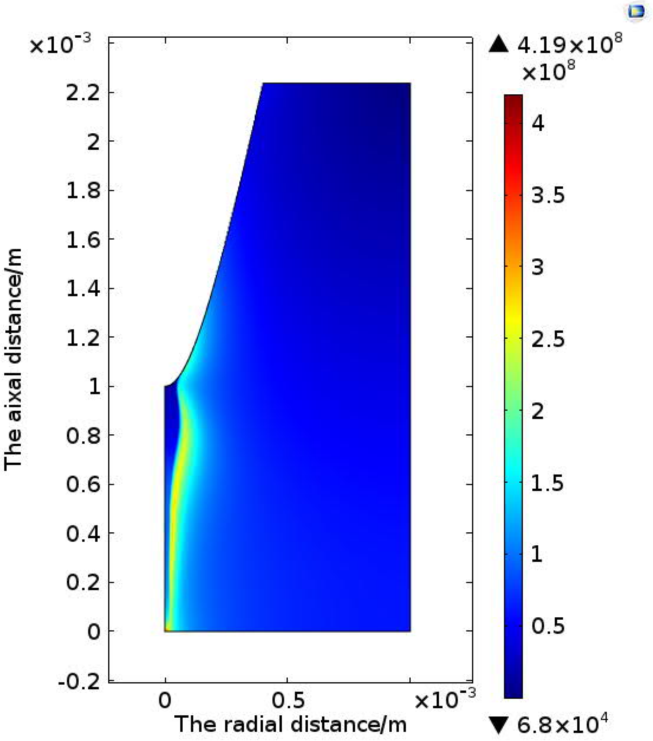
Fig.10 shows the temporal and spatial distribution of the electric field intensity in the oil at 10ns, 60ns, 120ns under above discharge condition. It is obvious that is a traditional streamer which propagates along the axis1 towards the plane electrode and finally breaks down.Fig.11 shows the distribution of electric field intensity along the axis 1 by Zener molecular ionization at 0, 10ns, 60ns and 120ns. At $t=0_+$, the pulse voltage is just applied. At that time, the electric field distribution is Laplace without the influence of space charge the peak of which is just at the needle. When the oil molecular are ionized, there are a lot of discharged particles at the pin-point. Then another electric field generated by the space charge adds on the Laplace field and distort it. Eventually the peak of the electric filed moves away from the needle toward the plane electrode, and the molecular ionization also moves forward with a form like “ionization wave”. After about 124ns, the peak of the electric field reaches the plane electrode together with the steamer, and breakdown happens. The maximum value of the electric field is about $4.23\times10^{8}V/m$[14].



t=10ns



t=60ns



t=120ns

Fig.10 The temporal and spatial distribution of the electric field intensity in the oil by Zener molecular ionization at 10ns, 60ns, 120ns

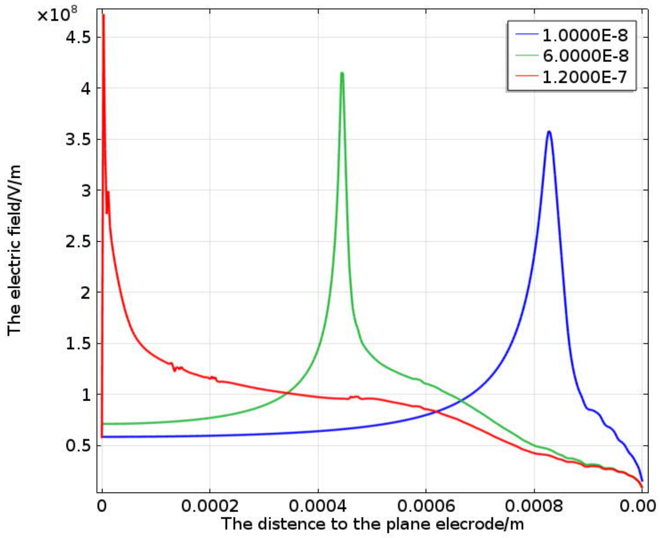


Fig.11 the distribution of electric field intensity along the axis 1 by Zener molecular ionization at 10ns, 60ns and 120ns

Fig.12 shows the distribution of space charge along the axis 1 by Zener molecular ionization at 10ns, 60ns and 100ns under above discharge condition. The oil molecules near the needle-point are ionized into positive ions and electrons. Because the mobility of electrons is higher, the electrons rush to the positive electrode fast. Thus an area of positive charge is formed by the remained positive ions at the front of the electron collapse. An additional field formed by these space charges significantly affects the original field inside the streamer plasma. The field ahead of the streamer is enhanced, which makes it much easier for the ionization of oil molecules in that area. This facilitates the propagation of the streamer channel towards the other electrode.

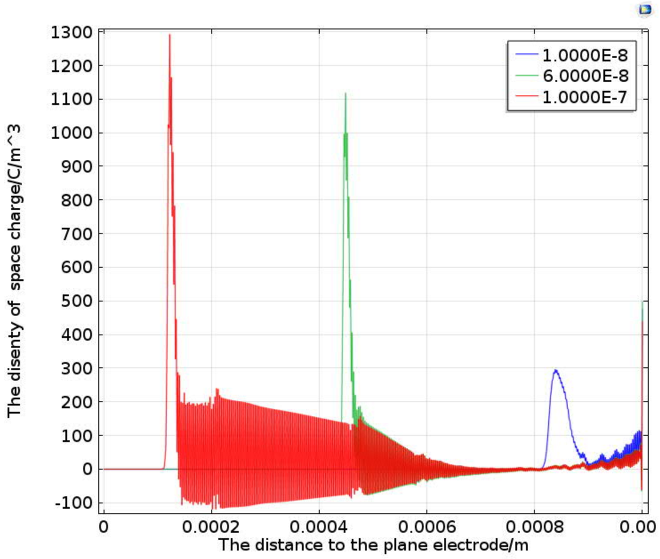


Fig.12 the distribution of space charge along the axis 1 by Zener molecular ionization at 10ns, 60ns and 100ns

Fig. 13 is the distribution of temperature along the axis 1 by Zener molecular ionization at 10ns, 60ns and 100ns under the above discharge condition. It is shown that the overall temperature of the oil is significantly increased by Zener molecular ionization. The reason is that, under the high voltage, large amount of charged particles are generated, which induces large discharge current and heat. This makes the considerable increase of oil temperature. This proves that the major factor for streaming discharge is the Zener molecular ionization.

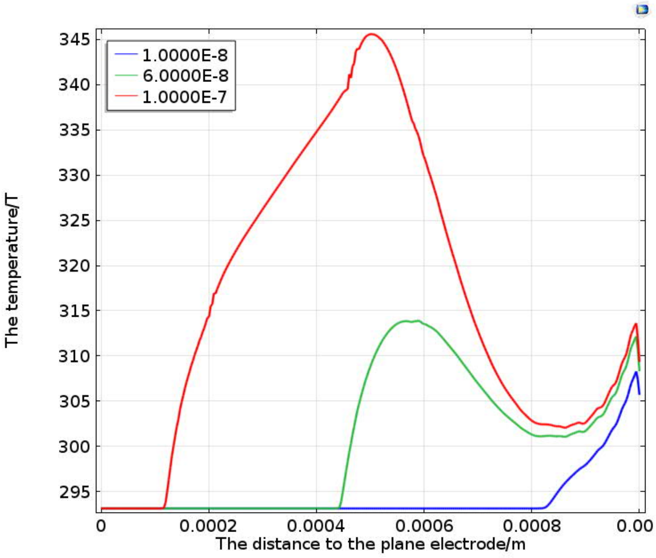


Fig.13 the distribution of temperature along the axis 1 by Zener molecular ionization at 10ns, 60ns and 100ns

Fig. 14 shows the distribution of electric potential along the axis 1 by Zener molecular ionization at 10ns, 60ns and 100ns under the above discharge configuration. It is shown that the fall of electric potential in the streaming channel is about 10^8 V/m, while the value measured in practical experiment is about 10^6 V/m. The reason of such mismatch is that, although the Zener molecular ionization is the major factor for oil discharge, it is not the only.

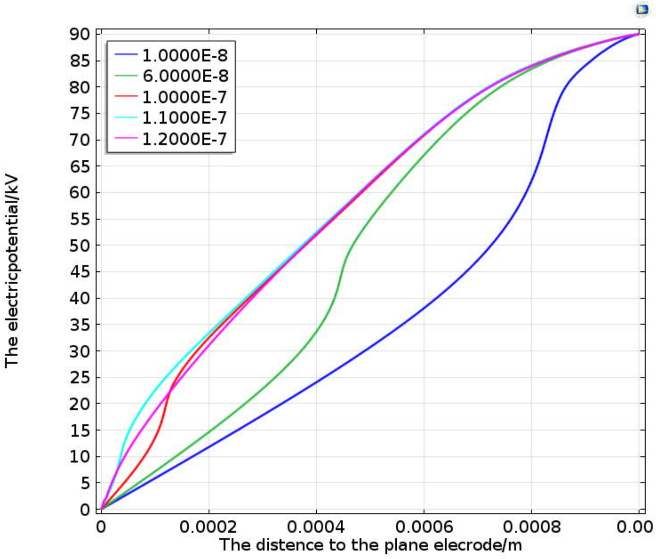


Fig.14 the distribution of electric potiential along the axis 1 by Zener molecular ionization at 10ns, 60ns and 100ns

D. The effect of impact ionization on transformer oil discharge by simulation

In order to get more comprehensive analysis of streamer inception and propagation, it is necessary to investigate the impact ionization in gas-phase streamer channel.

Fig. 15 shows the field intensity distribution along the symmetry axis considering the impact ionization in gas-phase streaming channel at time t=22ns. It is shown that the tail part of the streamer channel is gas-phase area, where the field intensity is about $15\times10^6 V/m$. It is much lower than that at the front part of the streamer ($5\times10^8 V/m$). This is because the mobility of free charge carrier (electron and ion) in the gas-phase area is higher than that in the liquid-phase area. It means that the conductivity is higher in the gas-phase part at the tail of the streaming than that in the liquid part at the front. In another word, the electric field is weaker in the gas-phase part than in the liquid-phase part. This simulation result accords will with the practical experiment [15]. Therefore, the impact ionization in the gas-phase streamer channel is also a main factor inducing streamer discharge.

Fig.16 shows the electric potential distribution along the axis 1 considering the impact ionization in the gas-phase streamer channel. It shows that the decrease of electric potential is $10^6 V/m$ in the streamer channel, which is lower than that in the Zener molecular ionization. As analyzed before, the conductivity in gas-phase area is higher, which corresponds to a smaller potential fall in that area. This simulation result accords well with practical experiment [16].

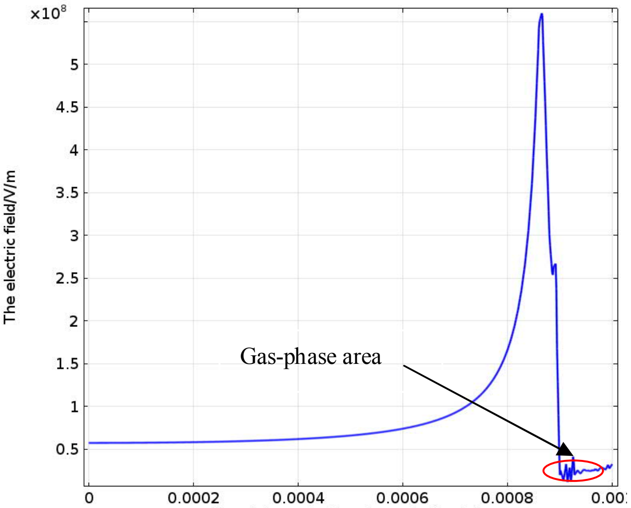


Fig.15 the electric field intensity along the axis 1 by impact ionization at 22ns

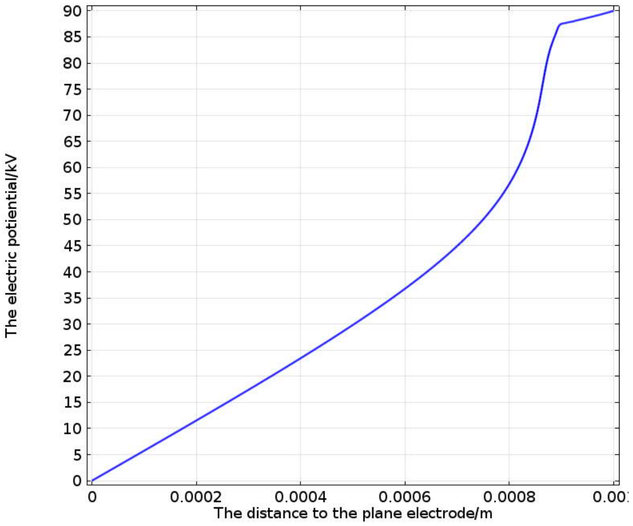


Fig.16 the electric potential along the axis 1 by impact ionization at 22ns

V. DISCUSSION

In this paper, three different mechanisms of charge generation are studied by simulation to evaluate their influence on the streaming discharge in transformer oil under high electric field. In the simulation of metal field emission and ionic disassociation, the oil temperature does not significantly increase and basically keeps around 300K. The reason is that only a few amount of charge is generated near the negative electrode including the electron and the free ions. The small discharge current induced by direct migration of such charge particles can only release a small amount of heat, which is not sufficient to cause significant change of oil temperature. Therefore, the metal field emission and ionic disassociation are neither the main factor inducing streamer discharge.

We establish the discharge model of Zener molecular ionization mechanism based on the Zener mode theory, and study its effect on streamer discharge. The spatial and temporal distribution of field intensity, space charge density, oil temperature and electric potential are obtained by simulation of our model. The simulation results indicate that large amount of space charge is generated near the needle-point, which significantly enhances the field intensity of that area. The peak of field intensity moves along the axial line towards the plane electrode, which forms the ionization wave along the axis 1. Such mechanism boosts the propagation of streamer discharge, and eventually leads to breakdown of the liquid dielectric. Large amount of charged particles are generated in this process, and the large discharge current releases lots of heat. The oil temperature increases significantly, which indicates that the field ionization is the major factor of discharging in transformer oil.

Besides, another factor should be considered that the electron impact discharge in low density area of streamer also has impact on the discharge, which is similar to the discharge in gas. We establish a liquid-gas two-phase model for its simulation. The space charge density and electric potential is calculated, and their spatial and temporal distribution is obtained by simulation, which accords well with the practical experiments. Therefore, it is proved that the electron impact ionization is also an important factor in transformer oil discharge.

VI. CONCLUSION

Systems simulation is a set of techniques that allows computers to imitate the operations of various real-world tasks or processes through simulation. Modern computers and super-computers are used to generate numeric models for the purpose of describing or displaying complex interaction among multiple variables within a system. Simulation analysis plays an important role in Systems Theory nowadays**.** In this paper, the 2-D axial symmetric field model is established for the simulation of the discharge between needle-plane electrodes in transformer oil under pulse voltage. The influence of metal field emission, ionic disassociation, Zener molecular ionization and impact ionization on the discharge injection and propagation is investigated respectively. The simulation results show a very low density of electron caused by tunneling effect even under the largest field intensity. Such weak density of space charge is not sufficient to ring notable change to the field distribution. It can only cause weak discharge near the needle, but cannot make the discharge propagate towards the plane electrode to form the streamer. Therefore, the metal field emission is not the major factor of discharge.

On the other hand, the ionic disassociation generates a certain amount of free ions. The field induced by those free ions is added to the original main field. But this effect is limited locally near the needle-point, and the ionization wave cannot be formed towards the plane electrode. The streamer discharge cannot be formed only by this effect, and it is not the major factor which determines the streamer discharge.

In the system simulation, it is revealed that the Zener molecular ionization generates large amount of space charge, which can significantly enhance the initial discharging. The enhanced electric field boosts the formation of ionization wave, which induces the ionization propagation along the axial line towards the plane electrode. The streaming is formed and eventually penetrates the internal between the needle-plane electrodes. The breakdown causes large discharge current, and the heat released makes a significant rising of the oil temperature. Therefore, it is conclude that the Zener molecular ionization is the dominating factor for streaming discharge in oil. Moreover, in the simulation it is observed that a gas-phase area of low density is formed by molecular ionization. There exists impact ionization by electron in this area, and the simulation results accord closely with practical experiments. Therefore, the impact ionization by electron is another important factor of streamer discharge.

References

[1] Mauricio Aljure, Marley Becerraand Mattias E Karlsson. On the injection and generation of charge carriers in mineral oil under highelectric fields. J. Phys. Commun. 2019, 3(4):15-27

[2] Li Yuan, Mu Hai-Bao, Deng Jun-Bo, Zhang Guan-Jun andWang Shu-Hong. Simulational study on streamer discharge intransformer oil under positive nanosecond pulsevoltage J. Acta Phys. Sin. 2013,62(13):96-108

[3] Jouya Jadidian. Charge Transport and Breakdown Physics inLiquid/Solid Insulation Systems. 2013, 102:150

[4] Wang Qi, Wang Meng, Wang Jue Yan and Ping. Two-phase streamer characteristics in transformeroil under nanosecond impulses voltages J.HIGH POWER LASER AND PARTICLE BEAMS 2020,32(12): 99-105

[5] Luo En-Ze, Liu Yun-Peng, Liu Wei-Dong, Chen Lu-Jun and Zheng Mao-Sheng. Modification of the Fowler-Nordheim Formula for Actual Emitters. J. ACTA ELCTRONICA SINICA. 1996, 24(3): 5-9

[6] R. A. Holroyd and Mark Allen. Energy of Excess Electrons in Nonpolar Liquids by Photoelectric WorkFunction Measurements. J. Chemical Physics. 2012 ,54(12): 5014-5021

[7]Jadidian J, Zahn M. Charge transport analysis in two-phase composite dielectric systems[J]. IEEE Trans Plasma Science, 2013, 41 (9): 2464-2474

[8] Shi Jian, Sima Wenxia, Yang Qing,et, al. Influence of initial condition on the propagation of streamer in transformer oil. Conference of Chong Qing Society of Electrical Engineering. 2012,8(3):877-882

[9]Yan Zhang. The insulation Technology of High votage. The Press of China Electric Power.2014:56-81

[10] IEC Standard #60897 Methods for the determination of lightning impulse breakdown voltage of insulating liquid[S] ,1987.

[11] Reference guide COMSOL Multiphysics 5.0a

[12]Y. Nakamura, K. Shinsaka and Y. Hatano, "Electron Mobilities and Electron-Ion Recombination Rate Constants in Solid, Liquid and Gaseous Methane," J. Chem. Phys.1983,78(9).

[13]Wang Tonglei, Zhang Qiaogen, Ni Lihe,et,al. Bubble model of cathode discharge initiation process in transformer oil[J]. High Voltage Apparatus. 2017,46(6):2042-2048

[14]A. Mozumder. Electron Mobility on Liquid Hydrocarbons: Application of the Quasi-Ballistic Model J.Chem. Phys. Letts. 1995, 233, 167-172

[15] Huang Wenli, Sun Guangsheng, Wang Jue, et, al. Progress in the study of breakdown mechanism about liquid dielectric[J]. High Voltage Apparatus. 2005,2131-134

[16]J. Qian, et al., "Analysis of Polarity Effects in the Electrical Breakdown of Liquids," J. Phys. D: Appl. Phys. 2006,39, 359-369