

DYNAMIC MODELING OF THE DIELECTRIC BARRIER EFFECT FOR HIGH VOLTAGE APPARATUS

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Abstract: The Dielectric barrier effect, means using of additional insulation layer (a barrier) placed between electrodes, can significantly increase the breakdown voltage of insulation gap. Charge accumulation on the surfaces of the barrier leads to changes in the electric field distribution and, hence, in the electric loading (potential drop) of the different parts of the insulation system. This paper presents a developed model for charge transfer in homogeneous electrode systems consisting of a gas gap between two parallel-plates. The electron conservation is described by the electron density continuity equation using the drift-diffusion approximation. The analogous equation is applied for electron energy conservation. The transportation of heavy species, means non-electron species, is formulated based on the mixture-averaged approximation. The source terms are extracted based on plasma chemistry. These equations are coupled with Poisson's equation for computing electric fields affected by temporal and spatial variations of space charges in the system. This model is used to predict the maximum insulation withstand voltage of gas insulated systems with barriers.

1 INTRODUCTION

The barrier effect was firstly reported in [1, 2] when studying discharges in air gaps. It means inserting an insulating solid material in gaseous dielectric or condensed media (liquid and solid dielectrics that results the increasing of breakdown voltage or time to breakdown. In spite of a great number of experimental works having been devoted to this problem in gaseous dielectric, the mechanism of the barrier effect is still not well known.

In [3] the barrier effects on the breakdown voltages of a rod to plate were studied experimentally for dc, ac, lightning and switching impulse voltages. The other papers on studying the barrier effect experimentally are those of [4-12]. The used geometry in these experiments are point/plate gap [3, 6, 11], rod/rod gap [4-5, 7, 9-10] and conductor-rod gap [4, 5], all of those are inhomogeneous.

In [12-15] a model based on the knowledge of efficient ionisation factor is developed for the computation of the electric field and potential in the presence of a space charge. The computation is performed in a point-barrier-plane air gap under a positive voltage using finite element method. The optimum position of an insulating barrier that increases the breakdown voltage of long air gaps under positive switching and lightning impulse waves is determined in [13] experimentally as well as theoretically using a predictive model of the positive discharge. In [16], existing models of the barrier effect and evaluation of the interface role in this effect are reviewed and analyzed. However all foregoing models have been mainly based on its static behaviour, taking into account the charges

deposited on the dielectric surfaces and calculating the electric field in the gap.

In this paper, a detailed model is presented to describe various steps of the barrier effect. In the proposed model, free electrons and heavy species transport equations, plasma chemistry and surface reactions are simultaneously solved with Poisson's equations. Because of the complexity of modelling, we focus here only on homogeneous geometry.

2 MATHEMATICAL MODEL

The discharge simulation model considered here consists of the fluid dynamic equations, continuity equations for electrons and heavy species, chemistry plasma and surface reactions that are simultaneously solved with Poisson's equation.

2.1 Transport Equations of Species

The transport equations for the charged species are as follows.

The electron conservation is described by the electron density continuity equation [17] by using drift diffusion approximation for the electron density flux :

$$\frac{\partial n}{\partial t} + \nabla \cdot (-\mu E n - \nabla(Dn)) = S, \quad (1)$$

where n is the electrons number density, μ and D are the mobility and diffusion coefficient, E is the electric field and S is the net electron source term. A detailed expression of S is given in *chemical kinetics and source term treatment* sub-section later.

Similar to the continuity equation, the energy equation is given by [17]

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla \cdot (-\mu_\varepsilon E n_\varepsilon - \nabla(D_\varepsilon n_\varepsilon)) + E \cdot (-\mu E n - \nabla(Dn)) = S_\varepsilon, \quad (2)$$

where n_ε is the energy density, μ_ε and D_ε are the energy mobility and diffusion coefficient and S_ε is the total energy transfer due to collisions.

Neutral, excited species and ions, named here heavy species, in plasma require a suitable transport equation. Suppose a reacting flow consists of $k = 1, \dots, Q$ species and $j = 1, \dots, N$ reactions. The equation for the first $Q - 1$ species is given by [18]

$$\rho \frac{\partial Y_k}{\partial t} + \rho(\mathbf{V} \cdot \nabla) Y_k = \nabla \cdot \mathbf{j}_k + R_k, \quad (3)$$

where $\mathbf{j}_k$ is the multicomponent species flux, R_k is the rate expression for species, $\mathbf{V}$ is the mass averaged fluid velocity vector, ρ denotes the density of the mixture and Y_k is the mass fraction of species k .

The mass flux $\mathbf{j}_k$ is given by (known as Fick's Law)

$$\mathbf{j}_k = \rho Y_k \mathbf{V}_k = -\rho D_{km} \nabla Y_k. \quad (4)$$

With making the simplifying approximation that the velocities of all species $j \neq k$ are equal, the mixture-averaged diffusion coefficient D_{km} can be calculated from [19, 20]

$$\frac{1}{D_{km}} = \sum_{j \neq k} \frac{X_j}{D_{kj}} + \frac{X_k}{1 - Y_k} \sum_{j \neq k} \frac{Y_j}{D_{kj}}, \quad (5)$$

where D_{kj} are known as binary diffusion coefficients. In a low-density limit, from kinetic theory those are given as [20]

$$D_{kj} \left[\frac{m^2}{s} \right] = 0.0188 \frac{\sqrt{T^3/W_{kj}}}{p \sigma_{kj}^2 \Omega^{(1,1)*}(T_{kj}^*)}, \quad (6)$$

where $W_{kj}(g/mol) = W_k W_j / (W_k + W_j)$ is the reduced molecular weight (W_k and W_j are molecular weight of species k and j , respectively), $T(K)$ is temperature, $p(N/m^2)$ is pressure, $\sigma_{kj}(\text{\AA}) = \sigma_k \sigma_j / (\sigma_k + \sigma_j)$ is the reduced potential characteristic length, and the reduced collision integral $\Omega^{(1,1)*}(T_{kj}^*)$ may be approximated by a fit as [20]

$$\Omega^{(1,1)*}(T_{kj}^*) = 1.0548 T_{kj}^{*-0.15504} + (T_{kj}^* + 0.55909)^{-2.1705}, \quad (7)$$

where $T_{kj}^* = k_B T / \epsilon_{kj}$ is the reduced temperature (k_B is Boltzmann's constant) and is a function of the reduced potential well depth. For nonpolar species,

$$\frac{\epsilon_{kj}}{k_B} = \sqrt{\left(\frac{\epsilon_k}{k_B} \right) \left(\frac{\epsilon_j}{k_B} \right)}. \quad (8)$$

2.2 Chemical Kinetics and Source Term Treatment

The list of the dominant reactions for Argon, as the gas filled in the gap, in the rate balance equations is given in table 1.

Table 1: Modelled Reactions

React	Formula	Type	$\Delta\epsilon(eV)$
R1	$e + Ar \rightarrow e + Ar$	Elastic	0
R2	$e + Ar \rightarrow e + Ar^s$	Excitation	11.5
R3	$e + Ar^* \rightarrow e + Ar$	De-excitation	-11.5
R4	$e + Ar \rightarrow 2e + Ar^+$	Ionization	15.8
R5	$e + Ar^* \rightarrow 2e + Ar^+$	Ionization	4.427
R6	$Ar^* + Ar^* \rightarrow e + Ar + Ar^+$	Penning ionization	---
R7	$Ar^* + Ar \rightarrow Ar + Ar$	Metastable quenching	---

$\Delta\epsilon(eV)$ is energy loss. For electron impact reactions, the cross section data with a Maxwellian form for Electron Energy Distribution Function (EEDF) is used to obtain the rate constants. The cross section data for Argon is obtained from [21]. The rate constants for R5 and R6 reactions is given $3.734 \times 10^8 m^3/(s.mol)$, and $1807 m^3/(s.mol)$, respectively [22]. Reaction rates for R1-R7 reactions are as follow.

$$\begin{aligned} \eta_{R1} &= k_{R1} [X_e] [X_{Ar}] \\ \eta_{R2} &= k_{R2} [X_e] [X_{Ar}] \\ \eta_{R3} &= k_{R3} [X_e] [X_{Ar^*}] \\ \eta_{R4} &= k_{R4} [X_e] [X_{Ar}] \\ \eta_{R5} &= k_{R5} [X_e] [X_{Ar^*}] \\ \eta_{R6} &= k_{R6} [X_{Ar^*}] [X_{Ar^*}] \\ \eta_{R7} &= k_{R7} [X_{Ar^*}] [X_{Ar}] \end{aligned}$$

where $[X_k]$ is molar concentration of species k and k_{Rj} is rate constant of reaction j . The rate expressions for species are as follow.

$$\begin{aligned} \eta_{Ar} &= -\eta_{R2} + \eta_{R3} - \eta_{R4} + \eta_{R6} + \eta_{R7} \\ \eta_{Ar^*} &= +\eta_{R2} - \eta_{R3} - \eta_{R5} - 2\eta_{R6} - \eta_{R7} \\ \eta_{Ar^+} &= +\eta_{R4} + \eta_{R5} + \eta_{R6} \end{aligned}$$

In addition to the volumetric reactions, the following surface reactions are implemented.

Table 2: Surface Reactions

Reaction	Formula	Sticking Coefficient
R1	$Ar^* \rightarrow Ar$	1
R2	$Ar^+ \rightarrow Ar$	1

According to Table 2, when ions and excited atoms reach the wall, those are assumed to change back to neutral Argon atoms. The rate of surface reaction is the rate of collision with the surface times the probability that a collision results in a reaction. The later term as the sticking coefficients are assumed equal to 1, see Table 2. The secondary emission coefficients for various interfaces are given for the considered geometry in *simulation results* section later.

3 SIMULATION RESULTS

The simulated geometry is shown here in Figure 1 including a small gap filled with Argon between two parallel metallic plates. An insulating sheet is inserted in the gap. The problem is reduced to one dimension by assuming the gap is much smaller than the diameter of the plates. A standard lightning impulse voltage ($1.2/50 \mu s$) of positive polarity as follows is applied.

$$u(t) = 1.034U(e^{-t/\alpha_1} - e^{-t/\alpha_2}),$$

where $t(\mu s)$ is time, $1/\alpha_1$ and $1/\alpha_2$ are 68.2 and $0.405 \mu s$ respectively [23], and U is the peak of the voltage amplitude.

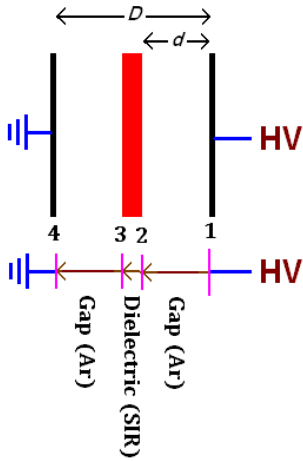


Figure 1: The simulated geometry

The insulating barrier is presumed to be silicon rubber (SIR) with relative permittivity of $\epsilon_r = 2.5$. The dielectric strength of the SIR is typically $20 kV/mm$. Initially a small number of electron seeds ($10^6 1/m^3$) is assumed to be present in the gap. This amount is equal to typically around free electrons in the air at sea level. Those are uniformly distributed in the gap length with the initial mean energy of 5 eV. The initial number density of Argon ions is assumed the same as the initial number density of electron seeds $10^6 1/m^3$. The secondary emission coefficients for surface reaction R1 in Table 2 are assumed to be 0, 0.01 and 0.25 in interfaces 1(anode), (2, 3 (barrier's surfaces)), and 4 (cathode). The mean electron energy of the emitted electrons, $\bar{\epsilon}_k$ is typically a function of the ionization energy of the impinging ions, $\Delta\epsilon_k$ (see Table 1) and the work function (W_f) of the surface:

$$\bar{\epsilon}_k = \Delta\epsilon_k - 2W_f \quad (9)$$

where W_f is presumed to be 5 eV here.

The Figures 2 and 3 show the free electrons number density and Argon ions number density in the gap respectively, and Figures 4 and 5 show the electric field and voltage distribution across the gap and the dielectric barrier. Here the dielectric barrier is in the middle of the gap. From Figure 2 and 3, it can be indicated that the generated free electrons and ions is more in gap at the side of the high voltage electrode than those at the side of the grounded electrode. It is more evident for ions.

This means that the dielectric barrier prevents of discharge development across the gap. The barrier has a thickness of 0.1 mm ($[2 \ 3] \times 10^{-4} m$) and the length of total gaps is 0.2 mm ($[0 \ 2] \times 10^{-4} m$ and $[3 \ 5] \times 10^{-4} m$) in Figures 2-5.

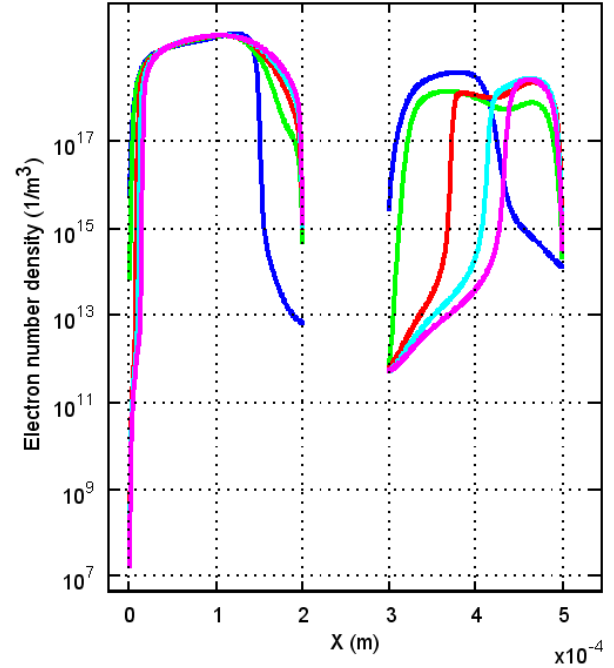


Figure 2: Electrons number densities for $1 \mu s$ (—), $3 \mu s$ (—), $5 \mu s$ (—), $7 \mu s$ (—), $9 \mu s$ (—).

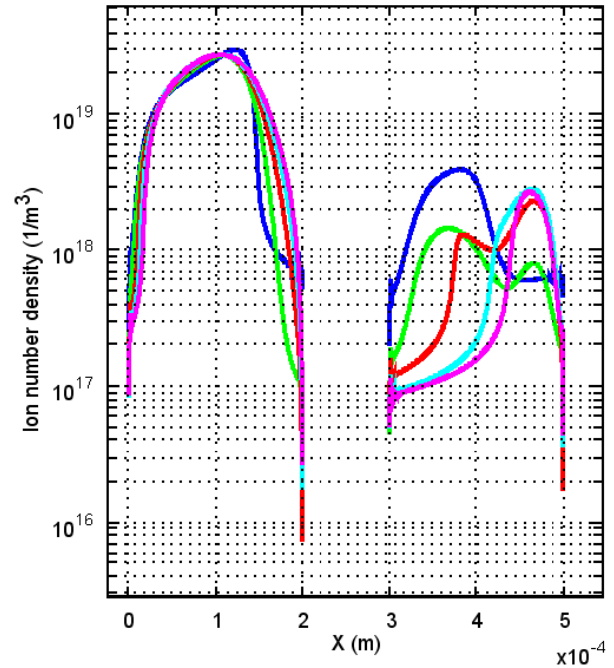


Figure 3: Ions number densities for $1 \mu s$ (—), $3 \mu s$ (—), $5 \mu s$ (—), $7 \mu s$ (—), $9 \mu s$ (—).

In Figure 4 the electric field across the dielectric barrier is enhanced and reached the point that is the dielectric strength. It is here $U = 2016.45V$ that can be considered as the breakdown voltage of insulating set.

Figure 6 shows the excited atom number densities for the gap. Analogous with behaviour of the densities for free electrons and ions, the densities of excited atoms at the side of the high voltage electrode is a little more than those at the side of the grounded electrode.

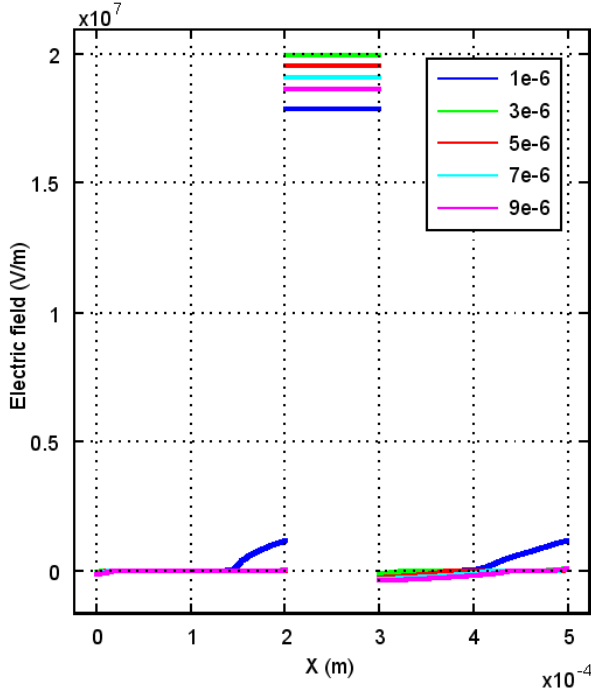


Figure 4: Electric field across the gap and the barrier for 1-9 μs

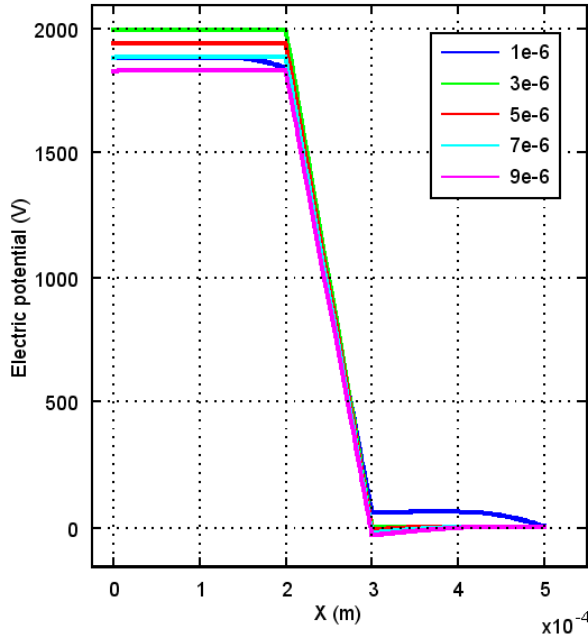


Figure 5: Voltage distribution across the gap and the barrier for 1-9 μs

Figure 7 shows the rate expression for the density of Argon ions, η_{Ar^+} . The same curves can be extracted for the excited atoms and the neutral atoms also those for reaction rates for R1-R7. From the Figure 7, it can be seen that the rate of generation of ions increase between 0.5 and 1.0 μs

(at 70-90% of crest value) due to high electric field of lightning impulse voltage and then it decreases.

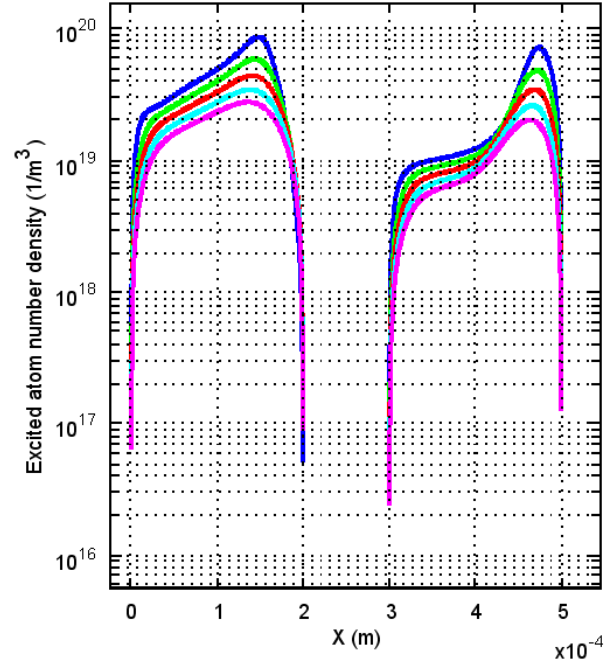


Figure 6: Excited atom number densities for 1 μs (—), 3 μs (—), 5 μs (—), 7 μs (—), 9 μs (—).

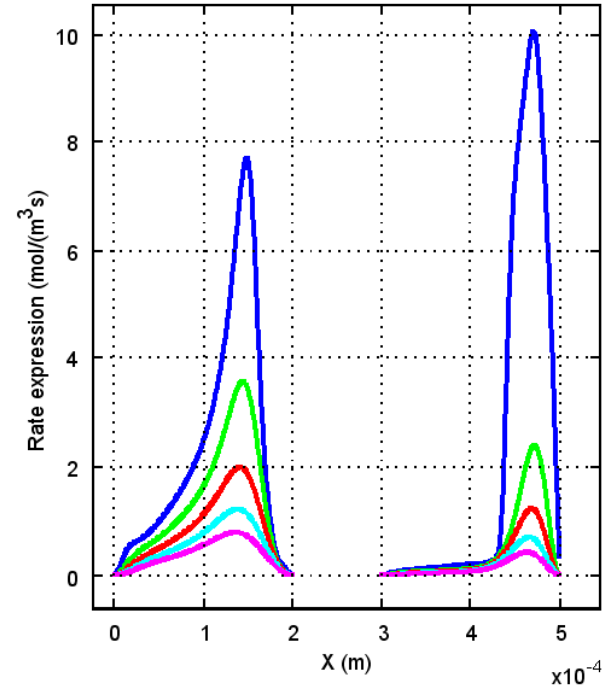


Figure 7: The rate expression for the density of Argon ions, η_{Ar^+} for 1 μs (—), 3 μs (—), 5 μs (—), 7 μs (—), 9 μs (—).

Based on Paschen's law for uniform field electrode gaps, the breakdown voltage is given [24]

$$V_{br} = \frac{B(pd)}{\ln[(pd)A] - \ln\left[\ln\left(\frac{1}{\gamma} + 1\right)\right]}, \quad (20)$$

where p is gas pressure, d is gas spacing, γ is the secondary ionization coefficient. Constants A and B for Argon are [24]

$$B = 235 \text{ [V/torr.cm]}, A = 13.6 \text{ [1/torr.cm]}.$$

About the considered example without dielectric barrier and with assumption the gap (with length of 0.5 mm) filled up Argon and in atmosphere pressure (760 Torr), the breakdown voltage based on Paschen's law is 1.7036 kV that is equals to an 3.3199 kV/mm electric field. In the simulated example here, the breakdown voltage is more than it without barrier, therefore the barrier effect improve the insulation performance.

Figure 8 shows the breakdown voltages for various situations of the barrier in the gap, d/D , regarding to Figure 1. The per cent of insulating improvement is given by

$$m = 100 \frac{V_{br} - V_{br1}}{V_{br1}},$$

where V_{br} and V_{br1} are the breakdown voltages with barrier and without it, respectively.

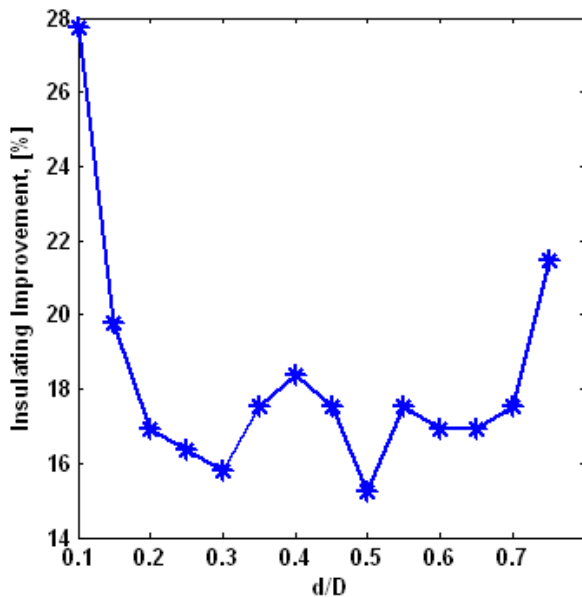


Figure 8. The breakdown voltages for various situations of the barrier in the gap

According to Figure 8:

- The barrier effect will improve the insulation performance from 15 % to more than 25%.
- Moving the barrier forward to high voltage electrode will increase the breakdown voltage.

Figure 9 shows the breakdown voltages for the geometry shown in Figure 1. The dielectric is placed in the middle of gap and the thickness is changed from 0.025 to 0.3 mm. The length of gap without barrier, D in Figure 1, is fixed to 0.5 mm. As seen from Figure 9, the more thickness of barrier, the more breakdown voltage is linearly resulted. Also In Figure 9 the breakdown voltage

without the barrier is presented based on Paschen's law and it can be seen that for the thickness less than 0.1 mm, the insulation performance will be weakened. On other hand, we have the insulation performance improvement for the thickness more than 0.1 mm.

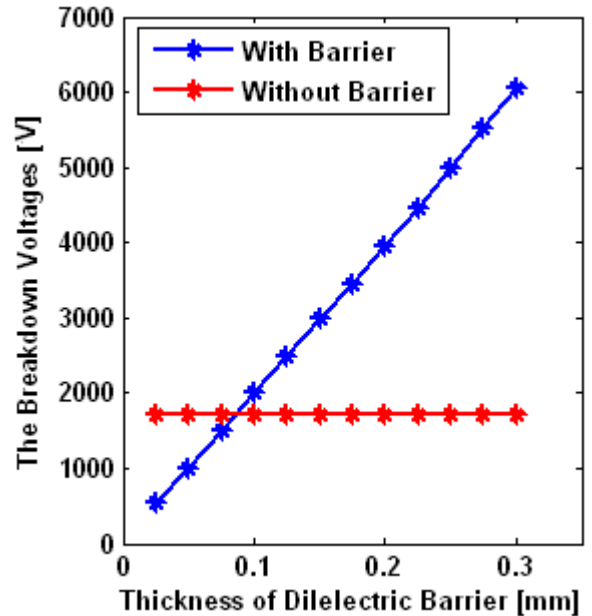


Figure 9. The breakdown voltages for various thicknesses of the barrier

4 CONCLUSION

The paper presents a detailed model to study the barrier effect with taking into consideration chemistry plasma, the electron and heavy species transport physics, and surface reactions. For electron transport modelling, the continuity equations for free electrons and their energies were solved accurately based on a Maxwellian EEDF and cross-section data of collisions. The transport phenomena for heavy species were modelled via a mixture-averaged formulation. In plasma chemistry, we consider the dominant reactions for the selected gas. It was showed that by moving the barrier toward the high voltage electrode and increasing of the thickness of dielectric barrier, the overall better insulation performance would be resulted.

5 REFERENCES

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