Study by simulation the influence of temperature on the formation of space charge in the dielectric multilayer Under DC Electric stress

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Abstract: Multidielectric polyethylene is a material that is generally employed as insulation for the HVDC isolations. In this paper, the influence of temperature on space charge dynamics has been studied, low-density polyethylene (LDPE) and Fluorinated Ethylene Propylene (FEP) sandwiched between two electrodes were subjected to voltage application of 5kV (14.3 kV/mm) for extended duration of time and the space charge measurements were taken using bipolar model is one-dimensional, taking into account trapping, detrapping and the rencommbinaison in order to determine the charge density and electric field of the sample depending on the thickness. The simulation was carried out at three different temperatures (20, 40, and 60°C). The results of this model going to compare with experimental space charge measurements . Finally, simulation results demonstrated that the temperature has many effects on the dynamic space charge and of influences the charge injection, charge mobility, electrical conduction, trapping and detrapping.

Keywords: Space Charge, Temperature, LDPE, FEP, Numerical Model.

1 Introduction

MULTILAYER polymeric insulation has been used in HVDC equipment for a long period time because it has economical cost and desirable electrical and physical properties. however, it degrades below a combined stress of thermal, electrical, mechanical, and chemical stresses during regular operations [1, 2]. When a direct-current (DC) voltage is applied to a polymer insulator lead to the presence of space charge formed in the bulk insulation inside the dielectric causes electric field distortions and may affect the degradation of the insulation system [3]. Therefore, a better understanding of space charge dynamics, in accordance with the particular variation of the space charge distribution in dielectric multilayer insulation becomes increasingly important and needs a careful investigation [4], we have taken the example of combination of two dielectrics Polyethylene Low Density (LDPE) and Fluorinated Ethylene Propylene (FEP) have been generally found in cable accessories between the insulation of the cable and that of the accessory in the high voltage (joints and termination) [5, 6].

However, the majority of the literature work has conducted at DC electric stress and at room temperature, especially, in a useful HVDC cable system [2], the operational temperature of HVDC cable is not constant, especially in countries where the climatic situation changes significantly during diffrent times of the year [7, 8]. For it becomes essential to study and attempt to understand space charge dynamics in the charge transport system of "sandwich" type LDPE-FEP under various temperatures under electric stress DC voltages. We have found much research to measure the dynamic of space charge in the dielectrics based on measuring systems such as the PWP, LIPP, and PEA methods [6-9]. For this selection, we have led to measure, understand and simulate the phenomenon of space charge in the dielectric multilayer at different temperatures. So we used a very complex model allows simulating the charge transport system of "sandwich" type LDPE-FEP. The purpose of this work is developed a numerical model based of the previous models [10-12], able to simulating the different experimental measures that describe the dynamic behavior of the space charge in the polyethylene insulation sandwich LDPE-FEP for the different temperature under stress 14.4 KV, based and compared with model [13], and investigated the effect of temperature on formation and stability of shallow trap at a dielectric interface of the multilayer under high DC electric field using the pulsed electroacoustic (PEA) technique, her results show that temperature plays a vital role in the space-charge dynamics at the dielectric interface, the applied DC voltage mainly effect the amount of space charge. For the calculation of the space charge and the electric field

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of our model, a description of our physical model then a numerical technique used to simulate the spaces charges profiles and electric fields and eventually, numerical results have gotten are analyzed with the experimental results.

2 Description of our model

We have followed the model proposed by Alison and hill in our model [14], we considered the charge transport is bipolar in an LDPE-FEP system sandwiched between a thick aluminum (Al) electrode and a semiconductive (Sc) electrode (carbonblack-loaded polyethylene film) system [10]. The injection of electrons in the cathode and the holes in the anode. Our model is asymmetric, one dimensional and the contact electrode polyethylene is supposed to be perfect. The traps are supposed to be distributed in a non-uniform way on the total thickness, and charge transport in the bulk of the dielectric with constant mobility under DC voltage application at the different temperatures [11, 13, 14]. The transport of charges is modeled by effective mobility independent of the electric field, taking into account the possible trapping and detrapping of charges in deep and shallow traps (short and long residence time, respectively) [15]. The principal characteristics of the model are described in Table 1. We have taken into account the trapping, detrapping and recombination, and we neglected the diffusion, the electric field applied in this work are considered meet the Schottky model and the mapping of the conduction mechanism is shown in Fig. 1, Where S_0, S_1, S_2 and S_3 are the coefficients of recombination; $p_{e\mu}$, p_{et}, p_{ht} and $p_{h\mu}$ are the carrier densities of charges; B_e and B_h are the coefficients of trapping; D_e and D_h are the coefficients of detrapping.

The total thickness d of the sample is 3.5 mm (The thickness of LDPE was typically = 2.5 mm, and that of FEP = 1 mm), it has sandwiched between two electrodes. The cathode is on the LDPE side, the anode on the FEP side. Fig. 2 shows the graphic representation of the LDPE-FEP system used for the computation. Where ε_1, ε_2 are the permittivities in LDPE and in FEP respectively.

Table 1 characteristics of the model [12, 13]

Characteristics	Model
General characteristics	Bipolar model
Trap levels	One level of deep traps
Transport	Effective mobility
Transport vs trapping	Trapping coefficients
	Detrapping barriers
Charge generation	Shottky injection
Charge extraction	No extraction barrier
Recombination	Recombination coefficients

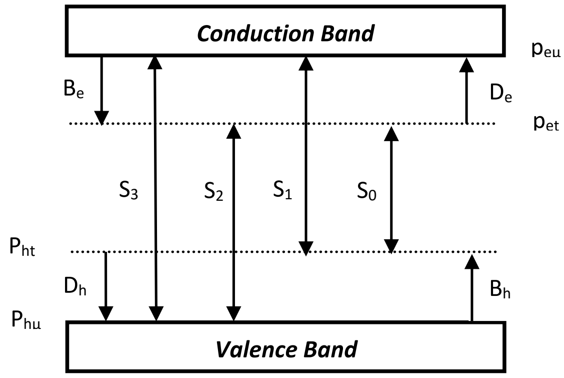


Fig. 1 Representation of the conduction mechanism trapping, detrapping and recombination of bipolar charges transport model.

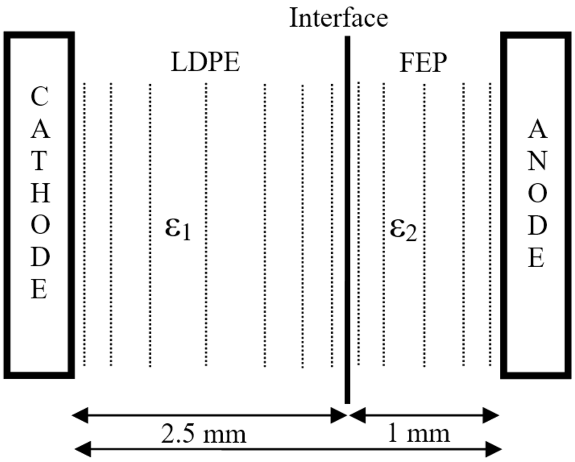


Fig. 2 Schematic representation of the LDPE-FEP system used for the simulation.

The modeling of each transport phenomena is based on the resolution of the same system of equations, which are the equations of continuity and of transport coupled to the Poisson's equation [11, 14]:

$$\frac{dE(x,t)}{dx} = x\,\frac{p(x,t)}{\varepsilon}\ ;0 > x > d \qquad (\text{Poisson}) \qquad (1)$$

$$E(x,t) = -\text{grad}\big(v(x,t)\big) \qquad (2)$$

$$\frac{dp_m(x,t)}{dx} + \frac{dj(x,t)}{dx} = S(x,t) \qquad (\text{Continuity}) \qquad (3)$$

$$j(x,t) = \mu(x,t).p_m(x,t).E(x,t) \quad (\text{Transport}) \qquad (4)$$

where t is the time and x the spatial coordinate. $E(x,t)$, $\mu(x,t)$ and ε are the electric field, the mobility of charge carriers and dielectric permittivity respectively. Therefore, the extraction fluxes for electrons at the cathode and for holes at the anode from the transport equation [16]. Where $p(x,t)$ is the net charge density:

$$p(x,t) = p_{h\mu}(x,t) + p_{ht}(x,t) - p_{e\mu}(x,t) - p_{et}(x,t) \qquad (5)$$

$p_{et}(x,t)$ and $p_{ht}(x,t)$ are densities of trapped electrons and holes respectively. $p_{e\mu}(x,t)$ and $p_{h\mu}(x,t)$ are densities of mobile electrons and holes respectively. $j(x,t)$: The fluxes and $S(x,t)$: The source term for trapping, detrapping and recombination electrons or holes which translates the appearance and disappearance of densities of each type of charges mobile or trapped not related to transport, These variations are represented by the following equations:

$$S_{e\mu} = -S_1 p_{e\mu}(x,t) p_{ht}(x,t) - S_3 p_{e\mu}(x,t) p_{h\mu}(x,t) - B_e p_{e\mu}(x,t)\left(1 - \frac{p_{et}(x,t)}{dp_{et}}\right) \quad (6)$$

$$S_{h\mu} = -S_2 p_{h\mu}(x,t) p_{et}(x,t) - S_3 p_{h\mu}(x,t) p_{e\mu}(x,t) - B_h p_{h\mu}(x,t)\left(1 - \frac{p_{ht}(x,t)}{dp_{ht}}\right) \quad (7)$$

$$S_{et} = -S_0 p_{et}(x,t) p_{ht}(x,t) - S_2 p_{et}(x,t) p_{h\mu}(x,t) + B_e p_{e\mu}(x,t)\left(1 - \frac{p_{et}(x,t)}{dp_{et}}\right) \quad (8)$$

$$S_{ht} = -S_0 p_{ht}(x,t) p_{et}(x,t) - S_1 p_{ht}(x,t) p_{e\mu}(x,t) + B_h p_{h\mu}(x,t)\left(1 - \frac{p_{ht}(x,t)}{dp_{ht}}\right) \quad (9)$$

$$D_{dt(e,h)} = \text{v}\exp\left(-\frac{W_{dt(e,h)}}{K_B T}\right) \quad (10)$$

where $S_{e\mu}$, $S_{h\mu}$, S_{et} and S_{ht} are source terms for mobile electrons, mobile holes, trapped electrons, and trapped holes respectively. d_{pet} and d_{pht} are the traps densities for electrons and holes. Where v=6×10^{12} s^{-1} is attempt-to-escape frequency [17], W_{Dte} and W_{Dth} are the dettraping barriers for electron and hole, respectively. K_B is the Boltzmann constant. All equations above are supplemented by the boundary conditions to interfaces and are written as [11]:

$$V(0, t > 0) = V_C \quad (11)$$

$$V(D, t > 0) = V_A \quad (12)$$

$$\Delta V = V_C - V_A \quad (13)$$

$$\int_0^D E\, dx = \Delta V \quad (14)$$

3 Generation of charges

All the charges are considered to be sourced from the Schottky injection from the limitations, injection of electrons at the cathode (LDPE), and holes at the anode (FEP). The injection of both types of carrier follows the Schottky law [10, 16]:

$$j_e(0,t) = AT^2 \times \exp\left(-\frac{e.w_e}{K_B.T}\right) \times \exp\left(\frac{e}{K_B.T}\sqrt{\frac{e.|E(0,t)|}{4.\pi.\varepsilon_1}}\right) \quad (15)$$

$$j_h(d,t) = AT^2 \times \exp\left(-\frac{e.w_h}{K_B.T}\right) \times \exp\left(\frac{e}{K_B.T}\sqrt{\frac{e.|E(d,t)|}{4.\pi.\varepsilon_2}}\right) \quad (16)$$

where $j_e(0,t)$ and $j_h(0,t)$ are the injected fluxes of electrons and holes at the cathode and anode respectively, A=1.2×10^6 Am^{-2}k is the Richardson constant, T is the temperature, ε_A and ε_B refer to the permittivity of LDPE (ε_1=2.2×ε_0) and (ε_2=2.1×ε_0) of FEP. w_e , and w_h are the injection barriers for electron and hole respectively.

4 Numerical techniques

4.1 Grid

The structure of the system considered is one-dimensional, the grid is asymmetrical function of the thickness of the LDPE-FEP system, is discretized non uniformly into n (n=301) equal elements of width Δx along its thickness, being tightened next to the electrodes and to the interface, to follow the penetration of the charge in the two dielectrics LDPE-FEP. The basic equations such as transport, continuity and Poisson equation have been solved, our numerical model used the finite element method with associated boundary conditions [16] in order to calculate the local electric field on the two dielectrics thickness and the Leonard model without the source terms, by using the boundary conditions related with the injected current fluxes (Equations (15) and (16)) [11, 12], two methods was applied to the Poisson's equation and the continuity equation respectively. The RungeKutta technique with fifth high order accuracy gives at any instant the distributions of two mobile and trapped space charge densities of electrons and holes generate the local net space charge density distribution [11], RungeKutta takes into account the source terms in Equations (6), (7), (8), (9) and (10) and initially the mobile space charge density. The difference between two permittivity of LDPE and FEP implies a discontinuity of electric field appears once in applies a voltage then to treat this discontinuity in the simulation based on calculating the electric field initial in each dielectric and add this value as the initial condition in the modeling. A quantification of the space charge positive $p_s(t)$ that has accumulated in the volume at t=60 mins (end of the phase of polarization) has been made in integrating the value of the charge measured in a thickness of insulation finished, in order to calculate approximately the dynamics of the charges at the dielectric interface according to the time in the case of polarization for diverse materials of electrodes, as follows, the capacitive charges at the electrodes are not taken into account [5, 18]:

$$p_s(t) = \int_{X_{\mathrm{LDPE}}}^{X_{\mathrm{FEP}}} \left| p_{\mathrm{trap}}(x,t) \right| \tag{17}$$

where X_{LDPE} and X_{FEP} are the starting point and the end point of the interfacial peak respectively. p_{trap} is the trap charge density takes in absolute value. We developed a program in Matlab to obtain numerical results for the equations and the physical conditions, its mentioned resolution procedure is repeated every time step to calculate all instantaneous profiles presented.

4.2 Results and discussion

For simulation, a DC potential of -14.3 kV is applied at temperature T = 20°C, T = 40°C and T = 60°C during one hour to the multidielectric structure an LDPE-FEP system, as presented in Fig. 2. The parameters used in our model are given in Table 2.

Fig. 3 represents the simulated net charge density and electric field profiles at the different time with an asymmetrical combination of. Fig. 3(a) illustrates the space charge formation for the two-layer LDPE-FEP sample. We have observed the appearance an interfacial negative charge appears in the dielectric interface LDPE-FEP, this charge increases with the duration of the polarization. This charge is clearly due to the

Table 2 Parameters used for our model

Parameters	Value	unit
Coefficients of trapping		
for electrons	7.10^{-3}	S^{-1}
for holes	7.10^{-3}	S^{-1}
Detrapping barriers		
for electrons	0.9	eV
for holes	0.9	eV
Thickness of the sample d	350	μm
The vacuum permittivity	8.5418782×10^{-12}	f/m
Recombination coefficients		
S_0	4×10^{-2}	$m^{-3}C^{-1}S^{-1}$
S_1	4×10^{-2}	$m^{-3}C^{-1}S^{-1}$
S_2	4×10^{-2}	$m^{-3}C^{-1}S^{-1}$
S_3	0	
Trap density		
dp_{et}	100	Cm^{-3}
dp_{ht}	100	Cm^{-3}
Mobility for		
electrons	7.10^{-15}	$m^2V^{-1}S^{-1}$
holes	2.10^{-15}	$m^2V^{-1}S^{-1}$

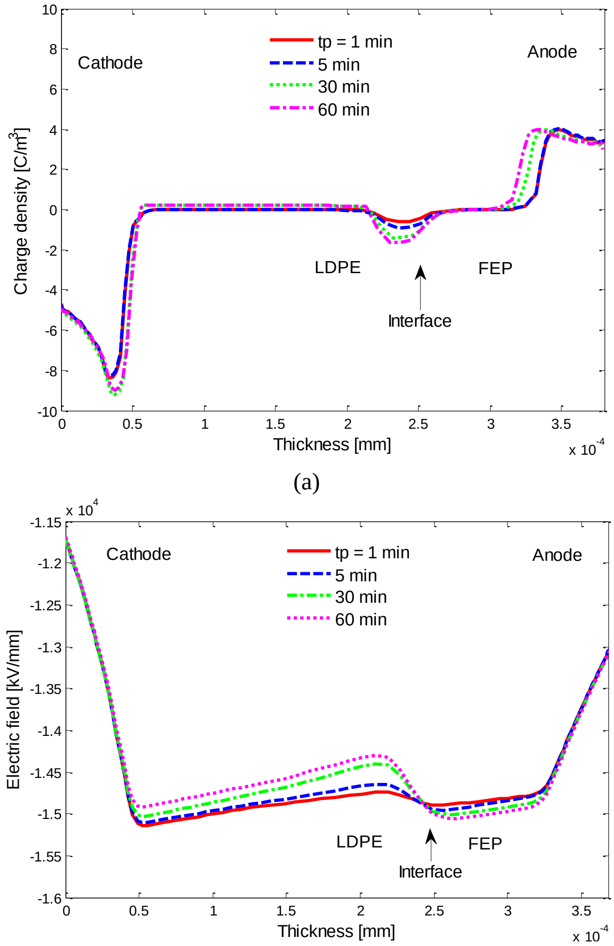


Fig. 3 Space charge and electric field distribution within a sandwich of LDPE-FEP with a negative charge at the dielectric/dielectric interface at T = 20°C: (a) Charge profile during polarization, (b) Electric field during polarization (T=20°C).

injection of the cathode electrode, and under the effect of electric field, the electrons move toward to the anode and blocked at the interface LDPE-FEP because the discontinuity and the conductivity. Also, we have seen petit positive charge accumulated next to the cathode electrode. The origin of the positive charge adjacent to the cathode can be explained as the positive charge injecting from anode into the sample an then moving towards (under the influence of the electric field) to the opposite electrode.

In the transport processing, the positive charge could meet the trapped electrons at the interface peak at a later stage. A positive charge is thought of as the charge with high mobility according our resultants. The Appearance of both positive and negative charges in the insulation causes a large distortion of the electric field distribution Fig. 3(b) The holes move through the dielectric via the cathode if we applied an electric field. A part of these holes are extracted to the electrode, cathode and the other party trapped in the LDPE layer.

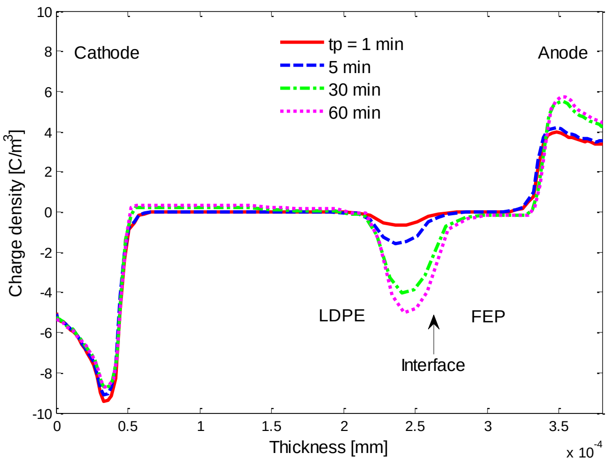
Fig. 4(a) represents the simulated net charge density profiles at the different time at T = 40°C. We have used an asymmetrically combined multilayer (350μm), this figure shows clearly that an accumulation of the interfacial negative charge in the first moment (at *t*=1 min) on the interface and increases strongly with the duration of polarization with a small amount of charge accumulated in the FEP layer. These negative charges due to the injection of the cathode electrode and under the effect of the electric field and the temperature, these electrons move towards to the anode. A significant part of this charge is blocked to the dielectric interface LDPE-FEP, and a small amount of this charge through the interface to be trapped in the FEP layer. There is a less positive charge accumulated next to the cathode electrode, this charge due to the injection of the anode electrode, and under the effect of the electric field, these holes move toward to the cathode electrode.

Fig. 4(b) shows that the electric field is strongly distorted because of the presence of great amount of the negative charges trapped at the dielectric interface of the LDPE-FEP, during the polarization time, the electric field in the FEP layer increases while the electric field in the LDPE layer decreases. The majority stressed part of the insulator is in the FEP, at near the anode electrode. The electric field in the volume of the dielectric will be deformed and can be calculated by the equation:

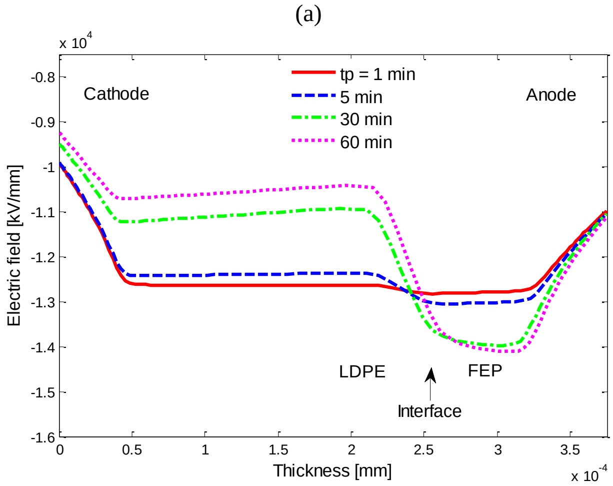
$$E_{\text{total}} = E_{\text{applied}} + E_{\text{sp}} \tag{18}$$

where Etotal is the electric field in the volume. $E_{\text{applied}} = U_0/d$ and E_{sp} are the applied stress and the stress from the space charge distribution, respectively.

Fig. 5(a) shows the simulated space charge profile at the LDPE-FEP dielectric interface at T = 60°C. It has clearly indicated the accumulation of the petit negative charge on the LDPE layer close to the cathode electrode (at t=1 min), negative charge increases with the duration of polarization. This charge due to the injection of the cathode electrode. Also, we have observed a petit amount of positive charge is accumulated in the LDPE layer close to the cathode, the origin of the positive charge would be due to the

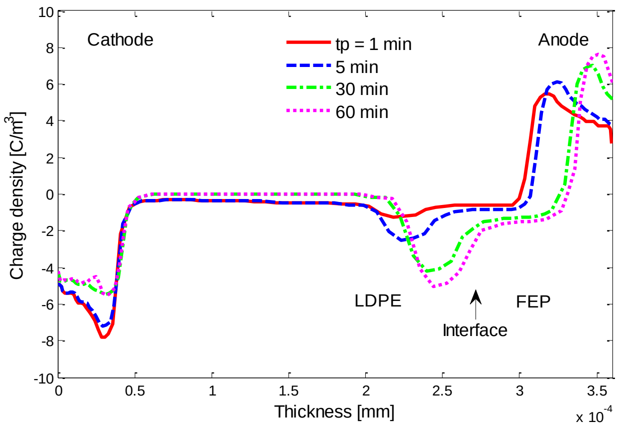


(a)

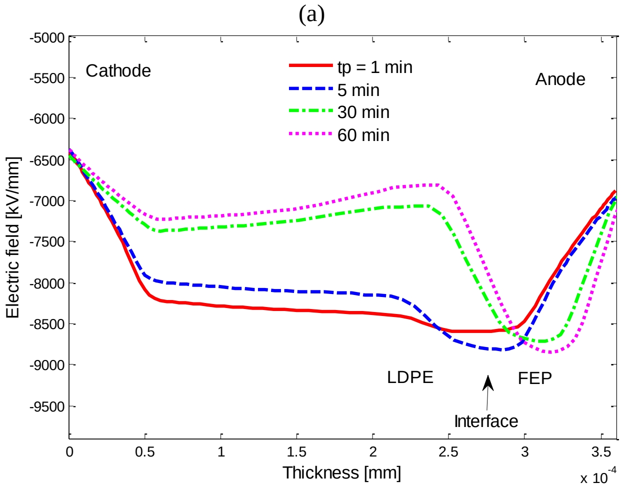


(b)

Fig. 4 Space charge and electric field distribution within a sandwich of LDPE-FEP with a negative charge at the dielectric/dielectric interface at T = 40°C: (a) Charge profile during polarization, (b) Electric field during polarization (T=40°C).



(a)



(b)

Fig. 5 Space charge and electric field distribution within a sandwich of LDPE-FEP with a negative charge at the dielectric/dielectric interface at T = 60°C: (a) Charge profile during polarization, (b) Electric field during polarization (T=60°C).

injection of the anode electrode in the case of the polarization, where it effectively compensates or recombines [13]. We have seen that the peak of the positive charge at the electrode anode moved to the right. Note the displacement of the peak due to high temperate. The presence of the charge interfacial, negative charge and positive charge in the structure of the dielectric deformed the distribution of the electric field Fig. 5(b)

Fig. 6 represents a comparison between the quantities of negative interfacial charges accumulated at dielectric interfaces LDPE-FEP for the different temperature of polarization within one hour. This figure has shown the temperature of T = 60°C and T = 40°C have a significant effect on the interfacial charge than T = 20°C. We can conclude at the effect of temperature these space charge may be charged win extra energy or the injected charges move quickly due to the mobility increase [8].

We have seen the existence two kinds of charge, the positive and the negative charge have distributed on the insulation multielectric shows clearly at the injection is produced by both the electrode. The amount of negative charge injected has increased with the increase of temperature. The amount of the positive charge accumulated in the LDPE layer at temperature T = 20°C is important than the quantity of positive charge accumulated at T = 40 °C and T = 60 °C (means that at elevated temperatures the polymer chains move on each other, such movement facilitates the movement of carriers of positive and negative charges). It is assumed that T = 40 °C and T = 60 °C, the amount of the filler positive is largely offset by the injected electrons from the cathode.

Also, we have noted that the decrease of the negative charge is faster than the decrease in the positive charge. It is assumed that the electron mobility in the LDPE is larger than the hole mobility in LDPE.

5 Conclusion

In this paper, the model more complex under DC high electric field of multidielectric LDPE-FEP sandwich system used for the different temperature has studied the effect of temperature on the characteristics of trapping in the insulators LDPE and FEP. The simulation results are resumed as follows:

- The simulation of the space charge and the electric field are clearly similar to the experimental results;
- The conductivity of the insulation dielectric is increased with the increase of the temperature, then the temperature is higher more fillers displacement of charge (electrons and holes) is fast.
- High temperatures have a significant effect on the training of the interfacial charge;
- The injection of the electrodes increases with increasing temperature, at high temperatures, the movements of polymer chains facilitates the movement of charge carriers.

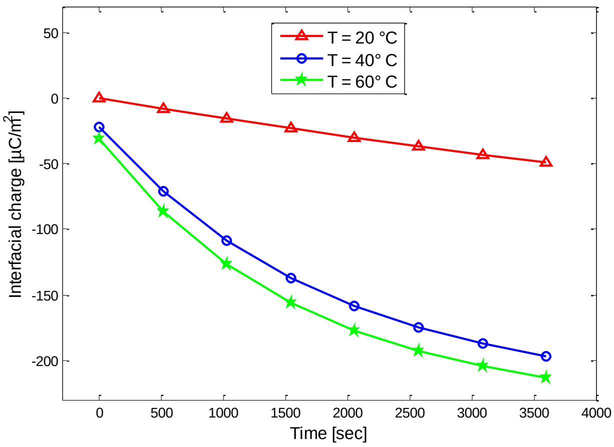


Fig. 6 Negative charge at the dielectric-dielectric interface subjected to field of 14.3 kV/mm for different values of temperature.

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