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Influence of Low Pressure on the Stability of Polypropylene Electrets Films

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1. Introduction

Electret is an important cross-scientific subject of dielectric physics, material science, sensor engineering, medical and bio-engineering (Sessler G., Sessler et al., Nalwa H., Goel M.). Over the years, considerable interest has been shown in the surface potential decay of corona-charged polymeric materials. Besides the electrets material and conditions of producing electrets the surface potential decay depends on number of factors under which the electrets have been stored or used, for example temperature, humidity, pressure etc. (Zhongfu et al., Gang-Jin et al., Ribeiro et al.).

The pressure effect has been investigated in number of papers. But there are only a few papers dealing with the influence of pressure lower than atmospheric on the electrets behaviour (Shepard et al., Wild et al., Gubkin et al., Draughn et al., Palaia et al., Mekishev et al., 2003, Mekishev et al., 2005). Moreover, the conclusions which have been made are contradictory. Some of the authors assume that charge decay is a result of sparking breakdown in the air according to Paschen's low and the others assume ions desorption from electret surface. Sheppard and Stranathan (Shepard et al.) investigated the effect of ambient pressure on the electret charge of thermoelectrets and showed that in the region of a few torr to 200 torr the charge of electrets increases proportionally to pressure. The linear dependence of the surface charge on pressure is in keeping with Henry's law of adsorption (Adamson et al.). Analogous linear dependence of electret surface potential on pressure in the range of 20 torr to 200 torr is observed in (Mekishev et al., 2003).

Wild and Stranathan (Wild et al.) studied the influence of external treatments on carnauba wax electret behaviour including the pressure effect in a wide range of pressures ranging from 10^{-5} torr to 3000 torr. Except for the plateaus at both low and high pressures, the curve obtained is similar to the curve of the sparking potential of air versus the logarithm of air pressure. Draughn and Catlin (Draughn et al.) investigated the effect of low pressure on surface charge of polystyrene and mylar electrets. All samples were stored with their surfaces exposed to the environment, i.e. unshielded. Authors conclude that the decrease in effective surface charge observed when electrets are exposed to low pressure is not the result of a spark breakdown between the electret surface and nearby conductors. The data indicate that the charge drops are due to ion desorption. After a discussion by B. Gross (Gross B.), Palaia and Catlin (Palaia et al.) investigated again the behaviour of oriented

polystyrene film and mylar electrets at low pressure. The results were found to be as predicted by the spark breakdown theory. It should be noted that in the papers referred above the method of dissectible capacitor was used to measure the effective surface charge. In (Mekishev et al., 2003, Mekishev et al., 2005) the electrets surface potential was measured by the vibrating-electrode method with compensation. The measurement system was located in a chamber connected to a vacuum pump and a vacuum gauge to measure the pressure in the chamber. After charging, the samples were placed in the measurement system and the initial electrets surface potential was measured. Then the pump produced low pressure, and the electrets surface potential vs storage time relationship at various pressure (20, 50, 100, 200 and 300 Torr) was measured for 1 h. It was shown (Mekishev et al., 2003) that the dependence of the surface potential on pressure is described by an equation which is analogous to the Langmuir law of adsorption. Furthermore, it was found in (Mekishev et al., 2005) that the time dependence of the electret surface potential at various pressures is described well by the differential equation for desorption. The authors proposed that ions desorption from the electret surface is most likely to occur. Polypropylene (PP) is one of the polymers, which has been widely used for preparing electrets, because of its excellent dielectric properties (Ono et al., Mohmeyer et al.).

The present paper reports the results of investigations on the low pressure effect on the behaviour of corona charged PP electrets. The PP films are charged in a positive or a negative corona at different charging temperatures: T=20^{o}C and T=90^{o}C. In the vacuum chamber some electrets were stored between two plate shorted electrodes with various air gaps and the other ones were put only onto a metal electrode. The time and temperature dependences of the surface potential of electrets were also studied.

2. Experimental

2.1 Used material and sample preparation

In the present paper isotactic PP films with thickness of 20μm produced by "Assenova Krepost" LTD – Bulgaria were investigated. Initially, the PP films were cleaned in an ultrasonic bath with alcohol for 4 minutes then washed in distilled water and dried on filter paper under room conditions. Samples of 30mm diameter were cut from the films. All the samples were put onto the same diameter metal pads.

2.2 Corona charging and surface potential measurement of the samples

The charging of the samples in a corona discharge was carried out by means of a conventional corona triode system (Jeda et al.) consisting of a corona electrode (needle), a grounded plate electrode and a grid placed between them – Fig. 1. The distance between the corona electrode and the grid was 10mm and the grid to grounded plate electrode distance was 3mm.

The samples 1 together with their metal pads were placed on the grounded plate electrode 4 and were charged for 1 minute at different charging temperatures (T=20^{o}C and T=90^{o}C). Positive or negative 5kV voltage was applied to the corona electrode 2. Voltages of the same polarity as that of the corona electrode from a power supply NB-825 were applied to the grid 3 and their values were 350V, 500V, 650V, 800V and 950V respectively. Electrets surface

potential was measured by the method of the vibrating electrode with compensation (Reedyk et al.) by which the estimated error was better than 5%.

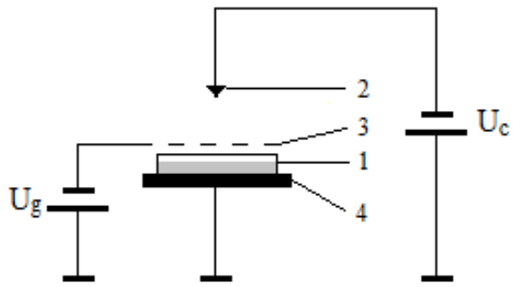


Fig. 1. Arrangement of the corona charging set-up.
1 – sample on a metal pad; 2 – corona electrode; 3 – grid; 4 – grounded plate electrode; U_g – grid voltage power supply; U_c –corona voltage power supply.

2.3 Low pressure treatment

After measuring the initial surface potential V_0, the samples, together with their metal pads, were placed for 30 minutes in a vacuum chamber under various low pressures.

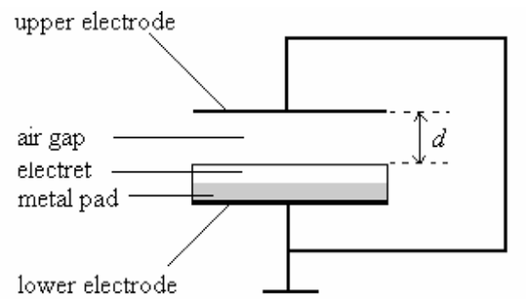


Fig. 2. Schematic diagram of the electret storage in the vacuum chamber between two short circuited plate electrodes (d is the air gap thickness).

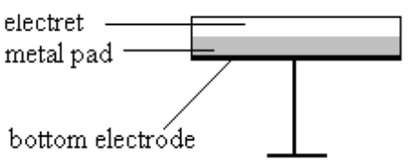


Fig. 3. Schematic diagram of the electret storage in the vacuum chamber in the absence of a second electrode.

The pressures in the vacuum chamber were 0.1mbar, 1mbar, 10mbar, 20mbar, 66mbar, 132mbar and 1000mbar. In the vacuum chamber the electrets were placed between two short circuited plate electrodes (Fig. 2) or deposited on metal pads in the absence of a second electrode (Fig. 3). After removing the electrets from the vacuum chamber, their surface potentials V were measured again and the normalized surface potentials V / V_0 were calculated.

3. Results and discussion

3.1 Results

3.1.1 Influence of the type of electrode

Two groups of experiments were carried out. The first group samples were non-metalized and placed on metal pads and the ones from the second group – metalized on one side. All samples were corona charged to the initial value of about 660V for the surface potential. The samples were then placed in a vacuum chamber at pressure of 0.1mbar for 30 minutes. The results obtained are presented in Table 1, where V_0 is the initial surface potential and V is the surface potential measured just after the samples were taken out of the vacuum chamber.

Samples	Surface potential		V / V_0
	Just after charging, V_0, V	After storage at 0.1mbar for 30 min., V, V	
Non-metalized	655±7	186±6	0.28±0.01
One-side metalized	671±7	189±7	0.28±0.01

Table 1. Surface potential for PP samples stored at pressure of 0.1mbar.

The results displayed in Table 1 show that the one-side metalized samples do not behave differently, compared with the non-metalized and placed on metal pads ones. In both cases the normalized surface potential decreases to about 0.28.

3.1.2 Charging time influence

The influence of the charging time on the surface potential of the electrets was studied. For that purpose the PP samples were corona charged using a three-electrode system (Fig. 1) at different charge time t_{ch} – 1, 5, 10, 20 and 30 minutes. The voltage U_c = -5kV was applied to the corona electrode and U_g = -650V to the grid.

Charging time, min.	V_0, V
1	657±7
5	664±6
10	660±6
20	650±5
30	648±9

Table 2. Surface potential of PP samples at different values for the charging time.

After the charging the initial surface potential V_0 of the samples was measured by the vibrating electrode method with compensation (Reedyk et al.). The measured surface potential values are presented in Table 2. The results obtained show that the charging time to 30 minutes does not influence the surface potential of the PP films.

3.1.3 Influence of the storage time under low pressure

The influence of sample storage time in the vacuum chamber on the surface potential decay was studied. For this purpose the samples were corona charged (Fig. 1) at a corona voltage of U_c = -5kV and a grid voltage of U_g = -650V. The initial surface potential V_0 was measured by the vibrating electrode method with compensation. Then the samples were placed in a vacuum chamber at a pressure of 0.1mbar at different time periods - 1, 15, 30 and 60 minutes. After the samples being taken out of the vacuum chamber their surface potential V was measured again. The results obtained are presented in Table 3.

Storage time at 0.1mbar, min.	Surface potential		V / V_0
	V_0, V	V, V	
1	642±9	187±21	0.29±0.04
15	639±9	184±18	0.29±0.03
30	648±5	172±5	0.27±0.01
60	646±4	177±20	0.27±0.03

Table 3. Surface potential of PP samples at different values of storage time, at 0.1 mbar.

It can be seen from the results in the table that the surface potential decreases within the first minute and that further storage at the reduced pressure does not bring any change. Based on the results obtained in parts 3.1.1, 3.1.2, 3.1.3 the next experiments were carried out with non-metalized samples being charged for a minute in a positive or a negative corona and being stored in the vacuum chamber for 30 minutes (for greater security).

The published papers discuss two main processes causing electret discharge at low pressure - sparking breakdown in air according to Paschen's law and ions desorption from electret surface. In order these processes to be studied two groups of experiments with different samples bonding were carried out. In the vacuum chamber the electrets were placed between two short circuited plate electrodes (Fig. 2) or deposited on metal pads in the absence of a second electrode (Fig. 3). The time and temperature dependences for the surface potential of polypropylene electrets charged in a negative corona at room temperature and temperature of 90^{o}C were also studied.

3.1.4 Electrets obtained in a corona charging and stored at low pressures between two short-circuited plate electrodes with various air gaps between the electrodes

All the samples were divided in five groups according to the thickness of the air gap. Each group was split into five series depending on the value of the initial surface potential.

The samples prepared were corona charged at room temperature by the three-electrode system (Fig. 1). Negative 5kV voltage U_c was applied to the corona electrode and to the grid – negative voltage U_g of 350V, 500V, 650V, 800V and 950V respectively. The electrets were thereby charged to different values of the initial surface potential V_0. After the samples were corona charged their initial surface potential was measured. Then the samples together with their metal pads were placed between two short-circuited flat electrodes, at a different thickness of the air gap (d – 0.10mm, 0.28mm, 0.84mm, 1.69mm and 3.00mm). The system

obtained in that way was stored in a vacuum chamber for 30 minutes at various low pressures - 0.1mbar, 1mbar, 10mbar, 20mbar, 66mbar, 132mbar and 1000mbar. For each of these pressures, after taking the samples out of the vacuum chamber their surface potential V was measured again. Normalized surface potential V / V_0 vs normalized pressure p / p_0 for negatively charged PP samples stored at two air gaps - d =0.10mm and d =3.00mm respectively - are presented in Fig. 4 and Fig. 5.

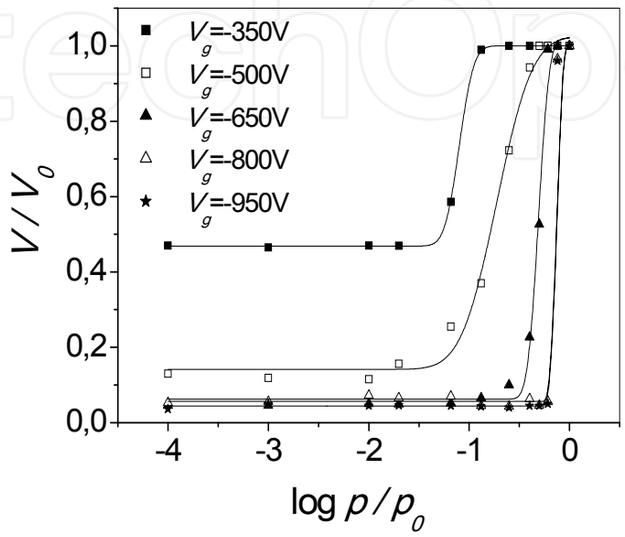


Fig. 4. Dependence of the normalized surface potential on normalized pressure for negatively charged PP samples. The air gap is d =0.10mm.

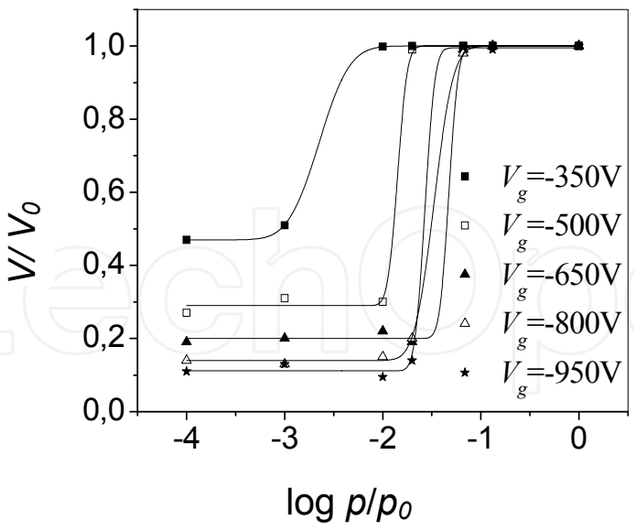


Fig. 5. Dependence of the normalized surface potential on normalized pressure for negatively charged PP samples. The air gap is d = 3.00mm.

Each figure point corresponds to an average value obtained by the measurement of 6 samples. The maximum deviation from the average values determined at confidence level

95% is 5%. The V_0 symbol stands for the initial value of the surface potential measured just after the samples charging and p_0 is the atmospheric pressure.

Analogous dependences were obtained for the other air gap values.

The results presented in Fig. 4 and Fig. 5 show the following features:

- For each curve three parts are observed. At high pressures the normalized surface potential stays constant and close to one (i.e. the surface potential at high pressures is approximately equal to the initial surface potential); at low pressures V / V_0 is also constant, however, with much lower values. For all the values of the initial surface potential, i.e. for all the series of samples there is a range of pressures within which the surface potential V_0 sharply decreases.
- The higher the initial surface potential, the higher the pressure at which the sharp decrease takes place, i.e. as the initial surface potential grows the curves are displaced to the right.
- With the increase of the air gap the decrease range is displaced to the lower pressures.

Table 4 presents the values of the normalized surface potential V / V_0 for samples stored at pressure of 0.1mbar between two short circuited plate electrodes at different thickness values d for the air gap.

U_g, V	V / V_0				
	d_1 =0.10mm	d_2 =0.28mm	d_3 =0.84mm	d_4 =1.69mm	d_5 =3.00mm
-350	0.47	0.44	0.46	0.45	0.47
-500	0.13	0.19	0.25	0.27	0.27
-650	0.05	0.07	0.11	0.14	0.19
-800	0.05	0.06	0.09	0.11	0.14
-950	0.04	0.06	0.07	0.09	0.11

Table 4. Normalized surface potential values V / V_0 (accuracy is better than 5%) for PP samples stored between two short-circuited plate electordes at the pressure of 0.1 mbar ($\log p / p_0 = -4$).

From the results presented in Table 4 the following conclusion can be made:
The final values of the surface potential at 0.1mbar decrease with the increase of the initial surface potential and grow with the increase of the air gap thickness.

3.1.5 Electrets obtained in a corona discharge and stored at low pressures in the absence of a second electrode

Two series of experiments with polypropylene samples were carried out. In the first one, the samples were charged in positive or negative coronas at room temperature, while in the second one they were charged in a positive or a negative corona at temperatures higher than the room one: 75°C and 90°C. The cleaning of the samples, their charging and the measurement of their surface potential were carried out as were described in 3.1.2. The

samples were stored in a vacuum chamber in the absence of a second electrode, i.e. in an air gap tending to infinity.

Normalized surface potential V / V_0 vs normalized p / p_0 pressure for samples charged in a positive or a negative corona respectively at room temperature are presented in Fig. 6 and Fig. 7, while the samples in Fig. 8 and Fig. 9 are charged in a positive or a negative corona respectively at temperature higher than the room one. As the electrets charged at 75°C and 90°C have the same behaviour the only presented results are the ones obtained at 90°C.

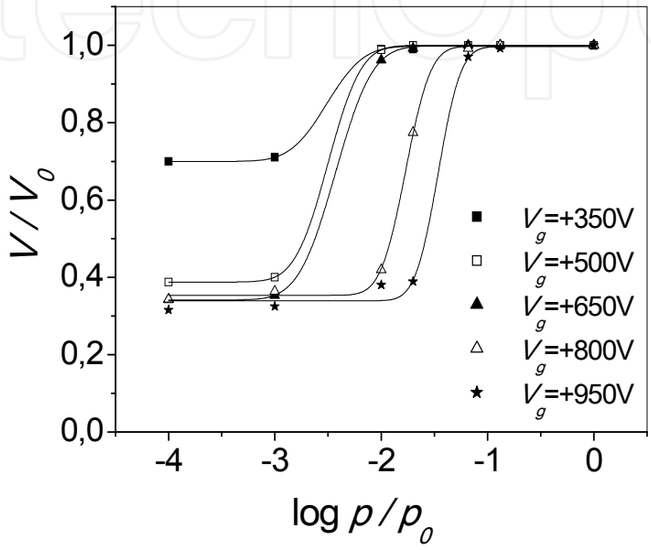


Fig. 6. Dependence of the normalized surface potential on normalized pressure for positively charged PP samples at room temperature. Infinite air gap.

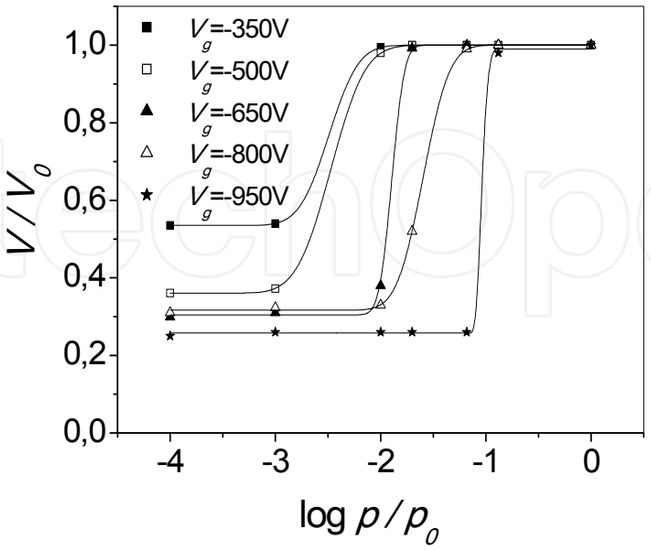


Fig. 7. Dependence of the normalized surface potential on the normalized pressure for negatively charged PP samples at room temperature. Infinite air gap.

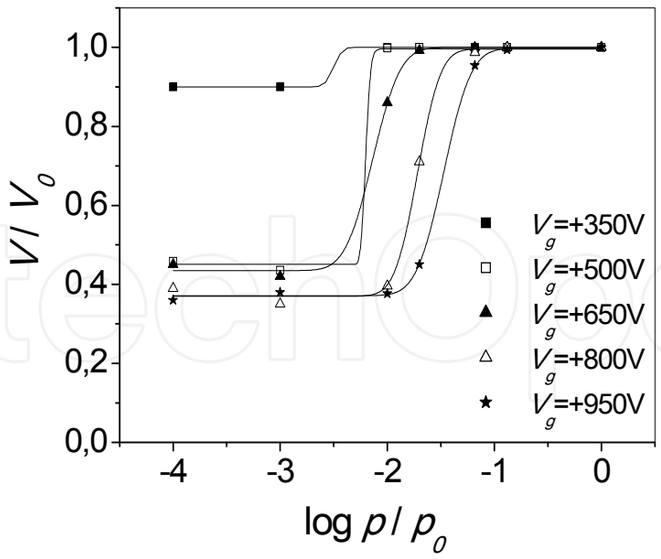


Fig. 8. Dependence of the normalized surface potential on the normalized pressure for positively charged PP samples at 90°C. Infinite air gap.

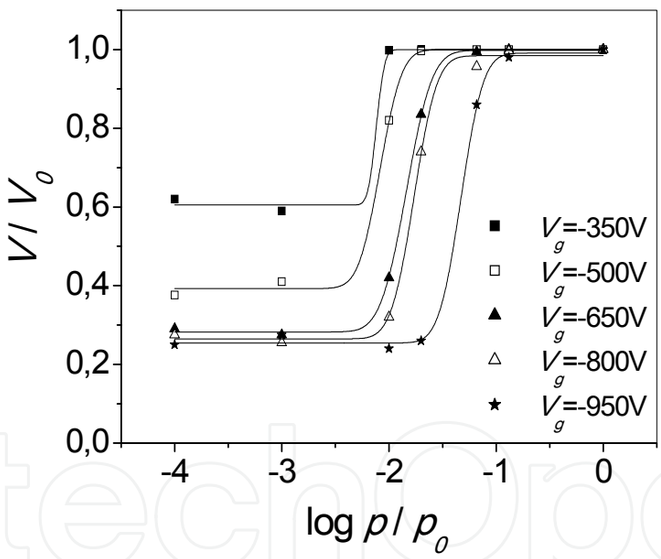


Fig. 9. Dependence of the normalized surface potential on the normalized pressure for negatively charged PP samples at 90°C. Infinite air gap.

Each point corresponds to the average value obtained by the measurement of 6 samples. The maximum deviation from the average values determined at 95% confidence level is 5%.

3.1.6 Time dependence of the surface potential of electrets obtained by corona charging and stored at low pressures in the absence of a second electrode

The storage time dependence on the decrease of the surface potential of PP electrets charged in negative corona at room temperature and at 90°C was studied. Voltage of U_c = -5kV was

applied to the corona electrode and to the grid - U_g = -800V. A part of the electrets obtained was stored at pressure of 0.1mbar for 30 minutes and after they were taken out of the vacuum chamber, their surface potential had been measured for 30 days. The surface potential of the other electrets had been measured in time just after their charging without preliminarily storage at low pressure.

The time dependence of the normalized surface potential for PP samples negatively charged at room temperature is presented in Fig. 10 and in Fig. 11 – for PP samples charged at 90°C.

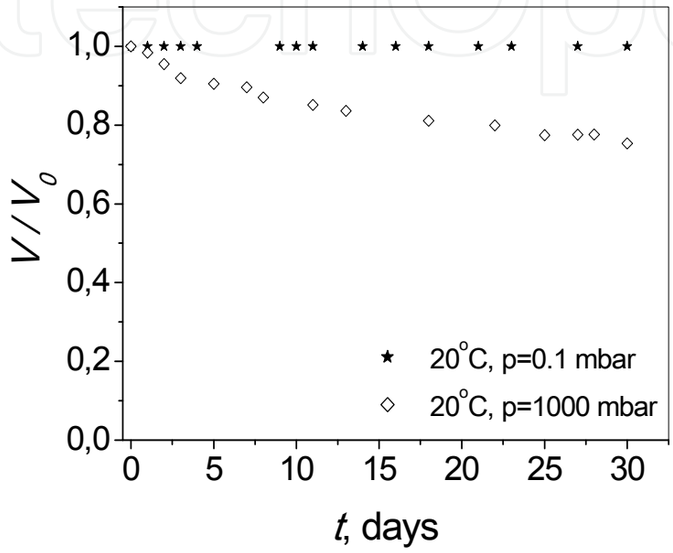


Fig. 10. Time dependence of the normalized surface potential for PP samples negatively charged at room temperature.

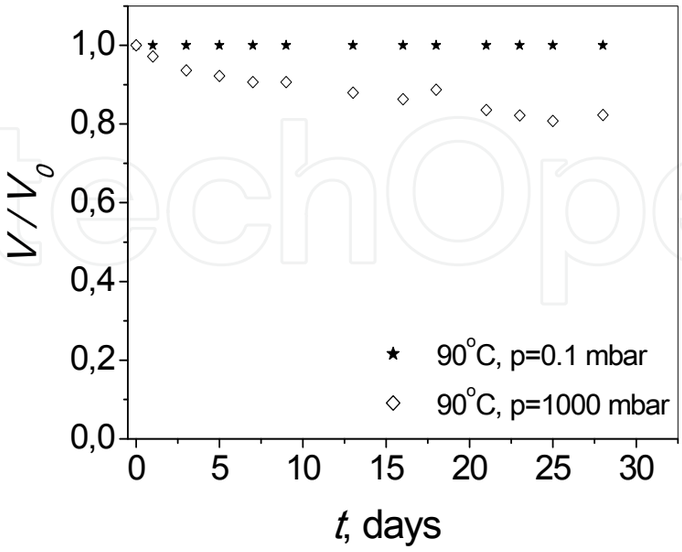


Fig. 11. Time dependence of the normalized surface potential for PP samples negatively charged at 90°C.

For each figure point the measured standard deviation does not exceed 10% of the average value at 95% confidence level.

It was found that:

- For samples preliminarily stored at pressure of 0.1mbar for 30 minutes the surface potential, independently of the charging temperature, does not change over time ;
- For samples which have not preliminarily been charged at low pressure the surface potential value decreases to a certain point over time.

Hence, the preliminarily placement of the electrets at low pressure for a certain period of time can be used as an effective method for stabilizing the electrets charge depending on their applications.

3.1.7 Temperature dependence of the surface potential of corona charged electrets

The dependences of normalized surface potential on the temperature for negatively charged PP films were investigated. Voltage of U_c = -5kV was applied to the corona electrode and to the grid - U_g = -500V. A part of the electrets was charged at room temperature and the other electrets – at temperature 90°C. The electrets obtained were preliminary stored for 30 minutes at two different pressures (0.1mbar and 1000mbar). After that the dependences of normalized surface potential on the temperature was measured.

The dependences of normalized surface potential on the temperature for negatively charged PP films are presented in Fig. 12.

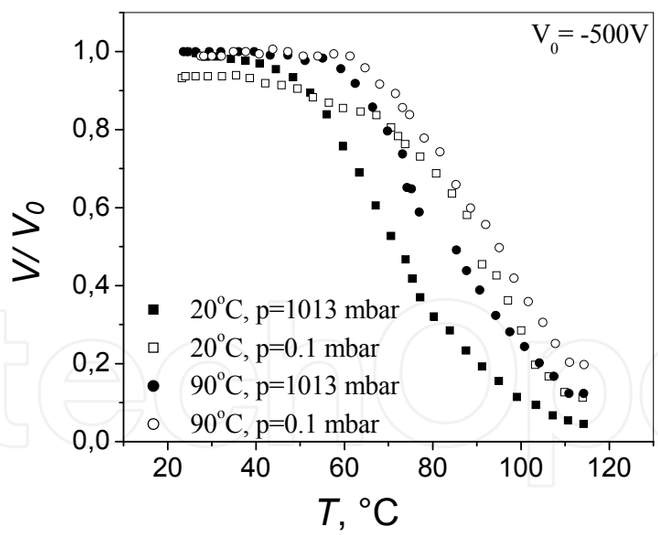


Fig. 12. Temperature surface potential decay curves after negative corona charge.

The results show that the curves of the samples which were preliminary stored at low pressure are shifted slightly to higher temperature as the shallow traps are liberated and the curves (Fig. 12) are shifted to higher temperature. When the temperature increases, the transport processes through the bulk will play a determinant role because of the increase of the injection of the carriers from the surface into the bulk and generating carriers in the bulk and the increase of their mobility.

3.2 Discussion

It is typical feature for the electret transducers that in most cases the electret is one-side metalized and is placed between two plate electrodes short-circuited by a resistor. The charged electret surface gives rise to an electric field in the air gap which is formed between the non-metalized electret surface and its adjacent electrode. This field can be found by an equation analogous to the one in (Palaia et al.):

$$E = \frac{\varepsilon V}{\varepsilon d + \varepsilon_1 L}, \quad (1)$$

where E is the air gap field, ε is the electret relative dielectric permeability, ε_1 =1 and d are the relative dielectric permeability and thickness of the air gap respectively, L - the electret thickness, V is the electret surface potential.

It is assumed in most of the papers that the electrets charge decay is due to gas discharges in the electret-electrode gap which depend on the gas pressure and the thickness of the gap itself according to Paschen's law (Knoll et al., Schaffert R.).

For dry air the Paschen's curve has a minimum at pd =6.65mbar.mm corresponding to a breakdown voltage of 360V (Schaffert R.). If the air gap field creates a voltage less than the breakdown voltage for the particular gas, gas discharges will not occur in the gap. When the air gap field creates a voltage equal or higher than the breakdown voltage, a discharge will occur and the electret charge will consequently decrease. The discharge will continue until the voltage across the air gap is reduced to a value below the minimum breakdown voltage for the respective value of the product pd and will not depend on both the size and the polarity of the initial electret surface potential as well as on the air gap thickness. Therefore, the minimal voltage value in the gap at which a discharge can be begun is 360V (Schaffert R.).

The values of the fields in and the voltages across the electret-electrode gap calculated for PP samples stored between two short-circuited electrodes with air gap thickness of 0.10mm are presented in Table 5.

Surface potential V, V	400	500	650	800	950
Electric field in the air gap E, kV/cm	36.7	45.9	59.6	73.4	87.1
Voltage in the air gap U, V	367	459	596	734	871

Table 5. Electric fields and voltages in a 0.10mm air gap at different surface potential values.

Analogous calculations have been made for the other gaps used in our experiments. In all cases the voltages in the gaps do not exceed the grid surface potential. At atmospheric pressure and various thicknesses of the air gap used in our experiments the pd values change from $pd_{\min}$ (d = 0.1mm) = 100 mbar.mm to $d_{\max}$ (d = 3mm) = 300 mbar.mm, which corresponds to breakdown voltages higher than 950V. Hence, the calculations show that at atmospheric pressure at different air gap thicknesses d the voltage across the air gap is less than the breakdown voltage according to the Paschen's law (Schaffert R.) for all thicknesses d studied and for all grid voltages U_g. Therefore, there will be no discharge.

When the pressure in the vacuum chamber decreases, the breakdown voltage also decreases, while the voltage across the air gap created by the electret practically does not change. Hence, the voltage across the air gap might be found higher than the one following from the Paschen's law and it may result in a discharge.

At pressure of 0.1mbar and air gap thicknesses from 0.10mm to 3.00mm, the pd product values lay in the (0.01-0.30)mbar.mm interval. These values are much lower than the 6.65mbar.mm value where a minimum of the Paschen's curve is observed and they correspond to a higher breakdown voltage than the minimal one of 360 V. Therefore, the air gap pressure curve will cross the Paschen's curve and the surface potential is expected to decrease to the minimal value of 360V corresponding to pd =6.65mbar.mm. However, the results obtained show that the surface potential has decreased to values considerably lower than the minimal pressure value following the Paschen's law. This can be seen from the curves presented in Fig.13.

The dependence of the minimal value $V_{\min}$ to which the surface potential at pressure 0.1mbar has decreased as a function of the initial surface potential V_0 for the different air gap thicknesses is presented in Fig. 13.

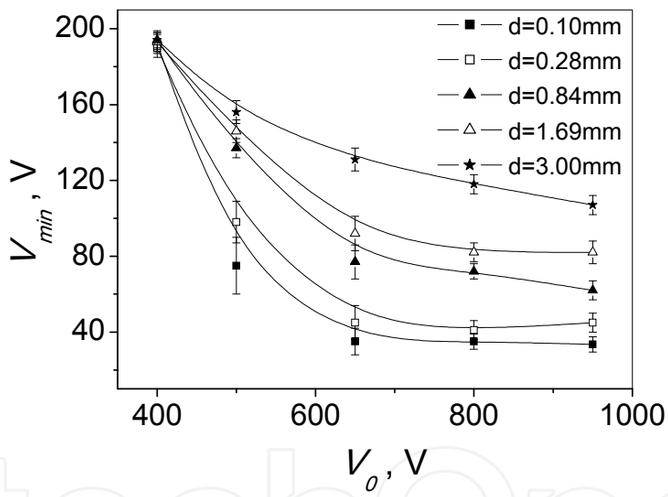


Fig. 13. Dependence of the minimum surface potential $V_{\min}$ on the initial surface potential V_0 at pressure of 0.1mbar for different air gaps.

Each figure point corresponds to an average value obtained by the measurement of 6 samples. The maximum deviation from the average values determined at 95% confidence level is 5%.

It can be seen from Fig. 13 that the surface potential decreases to a value lower than 360V for all values of the initial surface potential and all air gap thicknesses. With the air gap decrease and the initial surface potential increase the minimal value to which the electret surface potential decays is reduced. It decreases to a value of 33.5V at a gap of 0.10mm and initial surface potential 950V. This value of the surface potential corresponds to an electret-electrode gap voltage of 30.7V. This is considerably lower than the minimal value according

to the Paschen's law. On the other hand, it is supposed that as the initial surface potential decreases the minimum surface potential $V_{\min}$ tends to a value approximately equal to an initial surface potential of 300V. Some additional experiments were carried out in order to verify these values. Several series of samples were charged to an initial surface potential of 280V, 300V, 320V and 350V respectively. The electrets were stored at a pressure of 0.1mbar for 30 minutes. The gap between the electret surface and the upper electrode was 0.28mm. It was established that for samples charged to initial values of the surface potential 280V, 300V and 320V the normalized surface potential was 0.98 and for the ones charged to 350V – 0.61. Hence, if the initial surface potential value is approximately 300V, no surface potential decay takes place.

The analysis of the results obtained in different experiments shows that:

- First, discharges depend on the corona polarity and the charging temperature;
- Second, the surface potential decay process is analogous for both samples stored between two short-circuited electrodes with different air gap thicknesses and the ones with the absence of a second electrode;
- Third, the surface potential decreases to a value lower than the minimal breakdown voltage according to the Paschen's law.

If we assume that the charges obtained due to the corona discharge are located on the sample surface, we can calculate the charge surface density by the equation $\sigma = \frac{\varepsilon_0 \varepsilon}{L} U_k$.

When the electret surface potential is 950V then the surface charge density is equal to σ =9.25x10^{-8}C/cm^2. In this case the charges are found to be located at a distance thereabouts 13nm apart. When the electret surface potential is 350V this distance is thereabout 21nm. Therefore, there is a discrete charge distribution on the electret surface and it results in a nonuniform electric field having normal and tangential components, close to the surface (Neugebauer H., Pisanova et al.). At a distance three or four time larger than the distance between the charges, i.e. at a distance not greater than 80nm from the charged surface, the field is in fact homogeneous (Pisanova et al., Feynman et al.).

As it is shown in (Schaffert R.) the distribution of the electric field close to the charged surface is practically the same in both the presence and the absence of a second electrode. These results give an explanation to the similarity found in those cases when the electrets were stored in the absence of a second electrode (Mekishev et al., 2007, Viraneva et al.). It is established (Giacometti et al.) that during the corona discharge in the air, at atmospheric pressure, different types of ions are deposited on a sample while charging in a corona discharge depending on the corona polarity. In the case of a positive corona the ions are mainly $H^+(H_2O)_n$ and the ones for a negative corona - CO^{3-} (Giacometti et al.). Those ions are bound in traps of various depths and are released from them depending on the surrounding conditions. It was found in (Yovcheva et al.) by the X-ray photoelectron spectroscopy method that oxygen content in negatively charged samples is higher than that in positively charged samples. The oxygen content for non-charged samples is intermediate if compared to the values for the negatively and positively charged ones. It is assumed that the different oxygen content in the various cases is in consequence of various sorption processes on the sample surface. These results make us suppose that the main process responsible for the

surface potential decay can be associated with desorption of charged species from the electret surface under the influence of its own electric field. These might be ions deposited on the surface or groups in which the ions have given their charge away.

In the published papers one can see different models for explaining the adsorption (desorption) mechanisms. The experimental results were fitted by the Friondlih and Lengmuir equations in order to estimate how well these models describe the behavior of the surface potential of electrets stored at low pressure. The dependence of the normalized surface potential on the pressure for PP samples charged in negative corona at room temperature and stored between two plate electrodes with air gap thickness 3.00mm is presented in Fig. 14. One can see from Fig. 14 that the equations used do not describe the results obtained well enough. Analogous graphs were plotted for the other gaps (smaller than 3mm). It was established that for smaller gaps the fitting accuracy sharply decreases.

The dependences of the normalized surface potential on pressure for PP samples charged in a negative corona at room temperature and temperature 90°C to the initial surface potential value of 650V and stored in the absence of a second electrode are presented in Figs. 15, 16.

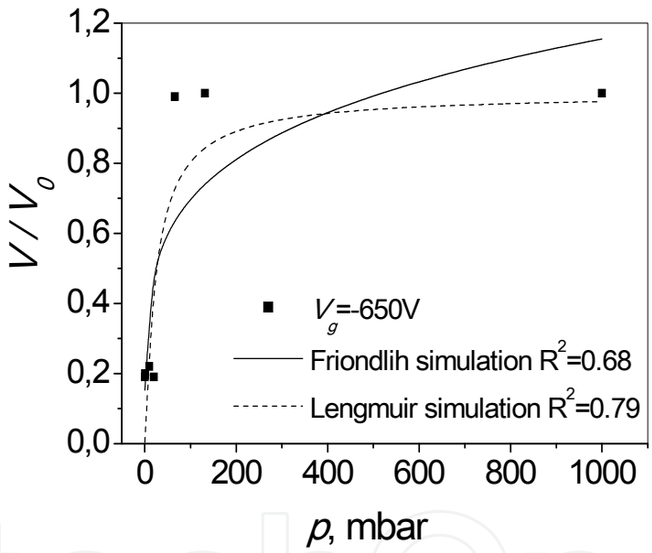


Fig. 14. Dependence of the normalized surface potential on pressure for negatively charged PP samples at temperature of 20°C, fitted by the Friondlih and Lengmuir equations. The air gap thickness is 3.00mm.

Analogous graphs were plotted for the samples charged in a positive corona.

The results presented in Fig.14-16 show that irrespective of the corona polarity and the charging temperature the Friondlih and Lengmuir equations do not describe very well the results obtained in our experiments as the determination factor is $0.36 \leq R^2 \leq 0.85$. That is why we assumed that the desorption process might run together with another process like charge movement along the surface, for example. Our assumption is based on the results reported in various papers (Protodyakonov et al., Baum et al., Karmazova et al., Atkinson et al., 1976, Atkinson et al., 1980, I, Atkinson et al., 1980, II) and some additional experiments we have carried out with electrets with an island charge distribution. It is reported in

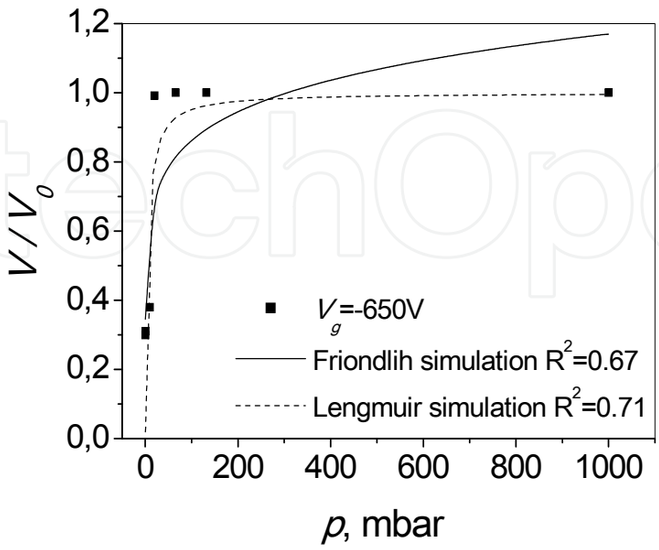


Fig. 15. Dependence of the normalized surface potential on pressure for PP samples charged in negative corona, at 20°C fitted by the Friondlih and Lengmuir equations. Infinite air gap.

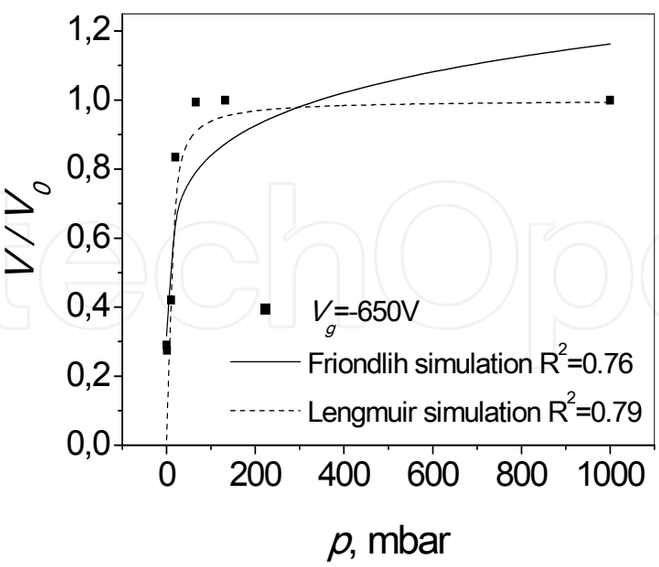


Fig. 16. Dependence of the normalized surface potential on pressure for PP samples charged in negative corona at 90°C, fitted by the Friondlih and Lengmuir equations. Infinite air gap.

(Protodyakonov et al.) that under certain conditions the adsorbate molecules located on the surface can be transferred along the surface without leaving it. The paper (Karmazova et al.) studies the influence of storage time on the surface potential decay for PP and PTFE samples with uniform and island charge distribution charged in corona discharge at room temperature and atmospheric pressure. It is shown that for samples with island charge distribution the surface potential decay is much smaller than for the ones with uniform charge distribution.

We carried out an experiment analogous to the one described in (Karmazova et al.): to charge PP samples in positive or negative corona we used a set-up for obtaining an island charge distribution described in (Karmazova et al.).

This set-up contains a grounded plate electrode, a metal mask (instead of a grid) with a numerous apertures of a definite size and distribution of the apertures and a corona electrode (a needle). The metal mask functions as a control electrode. During the charging process the polymer film was placed on the grounded plate electrode and the mask with the apertures was put on the film. The voltage U_c =±5kV was applied to the corona electrode and U_g =±650V – to the metal mask. The shape, the size and the distribution of the apertures in the mask define the shape, the size and the distribution of the charge on the electret surface (Fig.17).

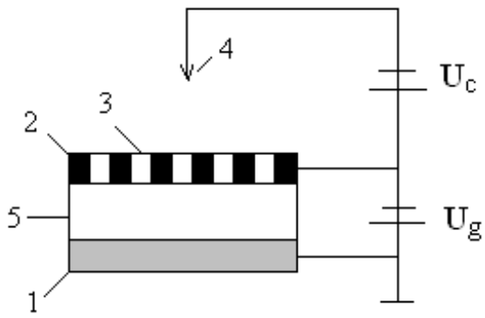


Fig. 17. Set-up for obtaining electrets with island charge distribution: 1 – grounded plate electrode; 2 – metal mask; 3 – apertures; 4 – corona electrode; 5 – electrets; U_c - corona voltage; U_g - metal mask voltage.

After obtaining the electrets the metal mask was removed from the charged film. The electret surface potential was measured by the method of vibrating electrode with compensation. Then the electrets were placed in a vacuum chamber for 30 minutes at various low pressures. After the samples were taken out of the vacuum chamber, their surface potential was measured again and the normalized surface potential V / V_0 was calculated. The dependence of the normalized surface potential V / V_0 on the normalized pressure p / p_0 for PP samples with island charge distribution is presented in Fig. 18.

Each graph point corresponds to the average value obtained by the measurement of 6 samples. The maximum deviation from the average values determined at 95% confidence level is 5%. The results for samples with island charge distribution stored at pressure of 0.1mbar are compared to the ones for samples with uniform charge distribution. These results are presented in Table 6.

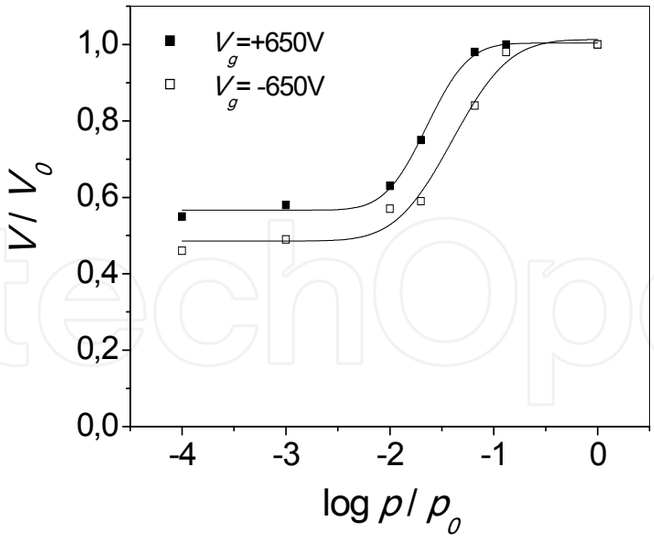


Fig. 18. Dependence of the normalized surface potential on normalized pressure for PP samples with island surface charge distribution.

Grid voltage	V / V_0	
	Uniform charge distribution	Island charge distribution
+650V	0.34	0.55
-650V	0.30	0.46

Table 6. Normalized surface potential V/V_0 values (with an error not exceeding 5%) for samples charged in positive or negative corona with uniform or island surface charge distribution. The samples were stored at pressure of 0.1mbar with the absence of a second electrode.

One can see from the table that when the samples were stored at pressure of 0.1mbar for 30 minutes the ones with an island charge distribution have higher surface potential values than the samples with uniform charge distribution, independent of the corona polarity. These results show that the assumption for the movement of the charges on surface seems completely plausible. The absorption and resorption currents in FEP teflon samples with 4.475 cm diameter are investigated in (Atkinson et al., 1976). One of the sample surfaces is completely metalized and an aluminum electrode with diameters ranging from 0.32cm to 2.54cm is evaporated in the central part of the second surface. The surface completely metalized is usually grounded and a definite voltage is applied to the upper electrode. It is established that there is a charge movement on the polymer surface between the metal electrode end and the non-metalized polymer surface. This movement is the main component of the absorption and resorption currents. The surface components of the absorption and resorption currents in vacuum for different polymers were later studied in (Atkinson et al., 1980 I). It was established for FEP teflon, polystyrene, polytetrafluorethylene and polythene that the charge movement along the polymer surface is the main component of these currents. Baum and coauthors were studied the surface

charge decay in PET films (Baum et al.). Using a corona discharge (positive or negative corona) a charged spot with a diameter of 0.5cm is created on one of the surfaces. It is established that the charges deposited by the corona source move laterally according to a diffusion law. The time dependence of the absorption currents is deduced in (Atkinson et al., 1980 II) on the assumption that these currents are entirely due to the transverse movement of charges caused by a concentration gradient of charge carriers. An equation combining linear desorption with surface diffusion is proposed for the description of some desorption processes in (Keltzev N.).

Our experimental results are well described by an equation analogous to the one in (Keltzev N.).

$$\theta = a + \frac{1}{2} b \left(1 + erf\left(\frac{x-c}{\sqrt{2}d} \right) \right), \tag{2}$$

where $\theta = V/V_0$ is the normalized surface potential, $x = p/p_0$ is the normalized pressure and a, b, c and d are constants depending on the charging conditions. Values of the parameters a, b, c and d for PP samples charged in positive or negative corona to an initial surface potential value of 800V are presented in Table 7.

Corona polarity	a	b	c	d
positive	0.3536± 0.0065	0.6439± 0.0085	-1.7702± 0.0076	0.1809± 0.0109
negative	0.3167± 0.0034	0.6835± 0.0053	-1.5964± 0.0088	0.1932± 0.0143

Table 7. Values of the parameters a, b, c and d obtained by fitting the equation 2.

The equation (2) is analyzed by using the $erf\left(\frac{x-c}{\sqrt{2}d} \right)$ values for different cases (Abramovich et al.). It should be noted that $d > 0$.

Case 1: $\left| \frac{x-c}{\sqrt{2}d} \right| >> 1$

a. $x - c > 0$

In this case $erf\left(\frac{x-c}{\sqrt{2}d} \right) = 1$ and from equation (2) it follows that: $\theta = a + b$ = const

Therefore, at high values of the ratio p/p_0, $\theta = a + b = 1$ and the surface potential practically remains equal to the initial surface potential, i.e. $V \approx V_0$. In this interval of the ratio p/p_0 no changes of the surface potential are observed.

b. $x - c < 0$

In this case $erf\left(\frac{x-c}{\sqrt{2}d} \right) = -1$ and from equation (2) it follows that:

$$\theta = a = const$$

Therefore, if $x < c$, the surface potential remains constant. Then the parameter a has the meaning of the minimum value of the normalized surface potential and b is the difference between the maximum and minimum values of the normalized surface potential.

Case 2: $\left|\frac{x-c}{\sqrt{2}d}\right| << 1$

In this case $erf\left(\frac{x-c}{\sqrt{2}d}\right)$ develops into a series and only the first linear term from the expansion can be considered:

$$erf\left(\frac{x-c}{\sqrt{2}d}\right) = \frac{2}{\sqrt{\pi}}\frac{x-c}{\sqrt{2}d}$$

and from equation (2) a linear dependence of θ on x is obtained:

$$\theta = A + Bx$$

where $A = a + \frac{b}{2} - \frac{bc}{\sqrt{2\pi}d}$ and $B = \frac{b}{\sqrt{2\pi}d}$.

If $x = c$, $erf\left(\frac{x-c}{\sqrt{2}d}\right) = 0$ and from equation (2) it follows that: $\theta = a + \frac{b}{2}$

Therefore, c is the midpoint of the range p / p_0 , within which the surface potential decay occurs.

When $x = c \pm \sqrt{2}d$, $erf\left(\frac{x-c}{\sqrt{2}d}\right) = \pm 0.843$, i.e. the decay range for the normalized surface potential is $\left(c - \sqrt{2}d, c + \sqrt{2}d\right)$.

All curves presented in Fig. 4-9 are described very well by equation (2) with a coefficient of determination $0.98 \le R^2 \le 1.00$. It was established that charging the electrets to various surface potential values leads to a curve displacement. The higher the initial surface potential the higher the pressure at which the sharp decay occurs. Therefore, there are two factors that influence the surface potential decay – the pressure at which the electrets have been stored and the initial surface potential to which they have been charged. The ratio p / V_0 is the main factor determining the surface potential decay range. Therefore, each group of experiments can be described by a generalized curve.

The dependences of the normalized surface potential V / V_0 on the normalized ratio $\left(p/V_0\right)^* = \left(p/V_0\right)\left(p_0/V_0^*\right)^{-1}$ for positively and negatively charged PP samples are presented in Fig. 19 and Fig. 20.(Mekishev et al., 2005)

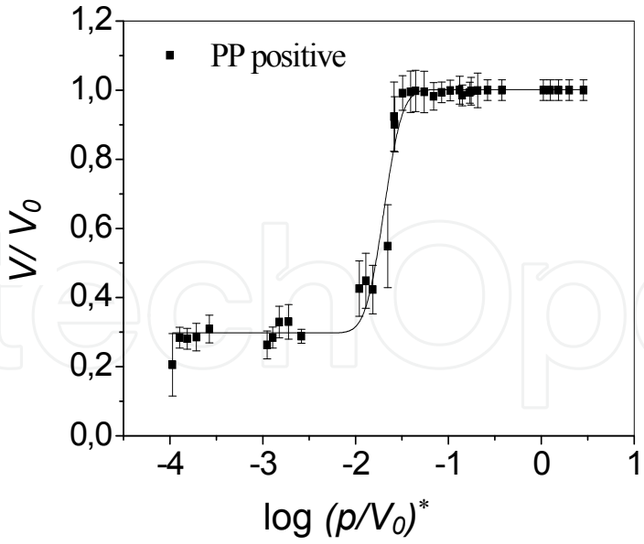


Fig. 19. Dependence of the normalized surface potential V / V_0 on the normalized ratio $(p/V_o)^*$ for positively charged PP samples.

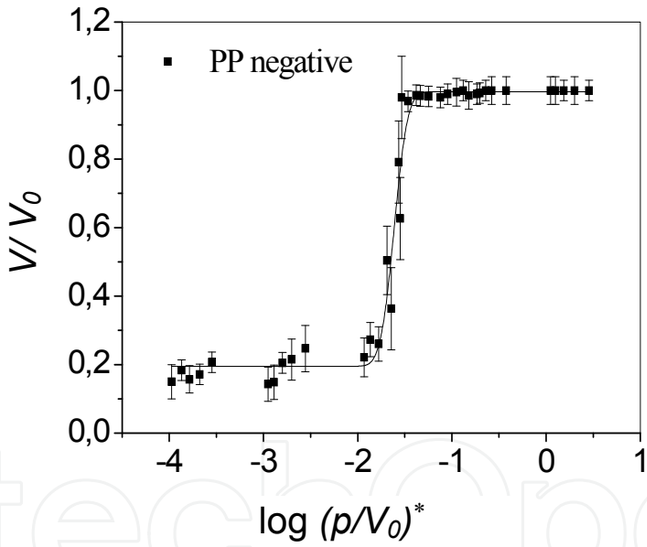


Fig. 20. Dependence of the normalized surface potential V / V_0 on the normalized ratio $(p/V_o)^*$ for negatively charged PP samples.

The symbol p_0 stands for the atmospheric pressure and $V_0^* = 1000$ V. For each graph point (Fig. 19, 20) the calculated standard deviation does not exceed 10% of the average value at 95% confidence level. It must be noted that the errors are smaller within the higher values of the normalized ratio $(p/V_o)^*$ and are higher in the range of the sharp decay.

It was found out that the results obtained can be described by an equation analogous to equation (2). The results presented so far are described very well with a coefficient of determination $0.98 \leq R^2 \leq 1.00$ by the following equation:

$$\theta = a^* + \frac{1}{2} b^* \left(1 + erf\left(\frac{x^* - c^*}{\sqrt{2} d^*} \right) \right), \tag{2a}$$

where $\theta = V/V_0$ is the normalized surface potential, $x^* = \log\left(p/V_0\right)^* = \log\left[\left(p/V_0\right).\left(p_0/V_0^*\right)^{-1} \right]$ and a^*, b^*, c^* and d^* are constants depending of the charging conditions. Values of this parameters for positively and negatively charged PP samples are presented in Table 8.

Corona polarity	a^*	b^*	c^*	d^*
positive	0.2977± 0.0153	0.7037± 0.0196	-1.6949± 0.0176	0.1508± 0.0214
negative	0.1950± 0.0167	0.8017± 0.0218	-1.6145± 0.0111	0.1051± 0.0159

Table 8. Values of the parameters a^*, b^*, c^* and d^* obtained by fitting the PP results by equation 2a.

It is seen from the results presented in Fig. 19, 20 and Table 8 that the minimum value of the surface potential after the sharp decrease is higher for the positively charged samples (higher values of parameter a^*). The values of the ratio p/V_0 for the midpoint of the region of the sharp surface potential decay were calculated using the values of parameter c^* from Table 8. The following values were obtained: 0.019mbar/V and 0.024mbar/V for the positively and negatively charged PP samples. Therefore, the ratio p/V_0 for the midpoint of the region, within which the sharp surface potential decay occurs, allows calculating the pressure at which the sharp electret surface potential decay will be observed if their initial surface potential is known.

4. Conclusion

The influence of low pressure on the behaviour of corona charged PP electrets was studied. The PP films were charged in a positive or a negative corona at different charging temperatures of T=20°C and T=90°C and were stored in a vacuum chamber under various low pressures. It was found that the charging time of 30 minutes does not influence the surface potential of the PP films. It was established that the surface potential decreases within the first minute and that further storage at the reduced pressure does not bring any change.

The analysis of the results obtained in different experiments shows that:

First, the surface potential decay depends on the corona polarity and the charging temperature; Second, the surface potential decay process is analogous for both samples stored between two short-circuited electrodes with different air gap thicknesses and the ones with the absence of a second electrode; Third, the surface potential decreases to a value lower than the minimal breakdown voltage according to the Paschen's law.

It is supposed that the main process responsible for the surface potential decay can be associated with desorption of charged species from the electret surface under the influence

of its own electric field accompanied by surface diffusion. An equation combining linear desorption with surface diffusion is proposed for the description of the surface potential decay. This equation described very well the results obtained with a coefficient of determination $0.98 \leq R^2 \leq 1.00$. It is proposed a generalized curve describing the dependence of normalized surface potential on the ratio p / V_0. From this curve it is possible to calculate pressure at which sharp decay will occur if the dependence of the surface potential on the pressure and the initial surface potential are known.

The preliminarily placement of the electrets at low pressure thereabout 1mbar for a certain period of time can be used as an effective method for stabilizing the electrets charge depending on their applications.

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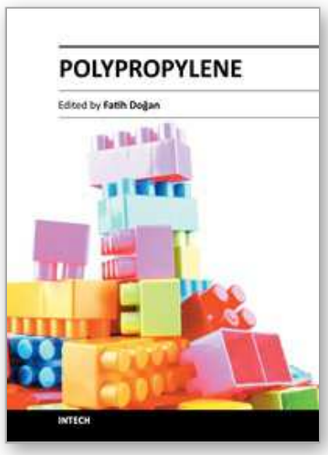
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Polypropylene

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This book aims to bring together researchers and their papers on polypropylene, and to describe and illustrate the developmental stages polypropylene has gone through over the last 70 years. Besides, one can find papers not only on every application and practice of polypropylene but also on the latest polypropylene technologies. It is also intended in this compilation to present information on polypropylene in a medium readily accessible for any reader.

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