**Electrıcal Strength and Electrıcal Conductıvıty of Polymer Composıtes**

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**Abstract.** This research investigates the electrical strength and specific volume resistivity of flame-retardant polymer composites (NFPC-30 and NFPC-10) under various temperatures using AC voltage and thermally stimulated depolarization current (TSDC) methods. Results indicate that NFPC-30 films demonstrate higher electrical breakdown strength in transformer oil than in air due to improved field homogeneity. The introduction of flame-retardant additives decreases the electrical strength but ensures compliance with standards for self-extinguishing polyethylene composites. Temperature-dependent measurements reveal that resistivity values decrease with increasing temperature, exhibiting a complex non-linear relationship due to enhanced macromolecular mobility at elevated temperatures. TSDC analysis enabled precise evaluation of resistivity at high temperatures, confirming the influence of additive concentration on dielectric behavior. Additionally, dielectric permittivity and loss tangent were measured, showing acceptable stability across tested frequencies and temperatures. Overall, the developed flame-retardant polymer composites demonstrate suitable electrical and dielectric properties for potential application in high-voltage insulation and electronic industries.

**Keywords:** polymer dielectrics, electrical breakdown strength, flame-retardant composites, temperature-dependent electrical properties, thermally stimulated depolarization current (tsdc)

# INTRODUCTION

Determination of electrical strength of polymer composites was carried out according to standards 6433.3-84 between flat stainless-steel electrodes. The diameter of the lower ground electrode was 50 mm, the upper electrode 10 mm. The test specimens were in the form of a disc with a diameter of 100 mm and a film thickness of 80-90 μm, the plates were 1 mm. The source of high voltage with a frequency of 50 Hz was a 2200x30000 V high-voltage transformer with a capacity of 2 kVA. The voltage on the sample was raised automatically at a rate of about 2 kV/s and was measured at the moment of breakdown using a C-96 kilovolt meter.

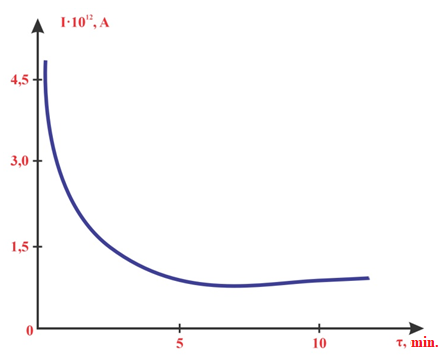
The wide application of plastics and synthetic resins in various industries has shown that along with their unique properties, they have a number of disadvantages. One of the most serious disadvantages inherent in such multi-tonnage polymers as polyolefin’s is their flammability. Therefore, the growth of production and consumption of many polymeric materials in various branches of technology, especially in the electrical and radio electronic industry, in construction, is somewhat restrained. Thus, the widespread use of polymeric materials has given rise to the acute problem of reducing their flammability. Reduction of flammability of polymeric materials is achieved mainly by their modification or introduction of combustion retardants - flame retardants [1, 2, 3].

# METHODS

The results of tests of polymer composites in the form of films and plates showed that the electrical strength of NFPC-30 (non-flammable polymer composite) film at room temperature in oil (105±4кV/mm) is almost 50% higher than in air (73±8кV/mm). This is due to the fact that the use of transformer oil increases the homogeneity of the electric field between the electrodes and reduces the possibility of partial discharges at the edge of the electrode. Tests of 1 mm thick plates at room temperature in oil showed that the introduction of additives in the polymer that reduce the flammability of polyethylene leads to a decrease in the electrical strength from 47 to 38 kV/mm.

According to the standard 16336-87 the electrical strength of PE composites for cable industry should be not less than 40 kV/mm at testing of samples with thickness of 1 mm, alternating voltage with frequency of 50 Hz in oil and 35 kV/mm - for self-extinguishing PE composites with thermal stabilisers and flame retardants (formulation additives 61K, 62K and 63K). Thus, it is established that the electrical strength of NFPC-30 composites, equal to 38 kV/mm, meet the requirements of standard 16336-87 for self-extinguishing PE composites resistant to thermo-oxidative ageing. In order to determine the possibility of development of reinforced film and sheet structural dielectrics using NFPC-30 as a binder DFPC (difficult flammable polyethylene composite), experimental work was carried out to investigate the compatibility of this composite with glass fibre fabric C-1189. It was established by the tests that the electrical strength of glass fabric C-1189 in air, as well as for NFPC-30 films, is significantly lower than in oil. The values of electrical strength of films consisting of NFPC-30 composite and one layer of glass fabric were lower than for NFPC-30 film. The breakdown of the glass fabric always occurred in the cell between the glass fibres. Therefore, it is possible to increase the electrical strength of the glass fabric by increasing the number of alternating layers of polymer-glass fibre so that the electrically weak places do not coincide.

In addition to the electrical strength, the character of change in the specific electrical resistance (ρV) of DFPC was also investigated. The typical time dependence of the charging current for the NFPC-30 film is presented in Figure 1. Based on the results of measurements performed on 4 samples, the values of ρV for NFPC-30 at the indicated temperatures were calculated.



**FIGURE 1.** Dependence of charging current on time for a 90 µm thick NFPC-30 sample (T = 700 C)

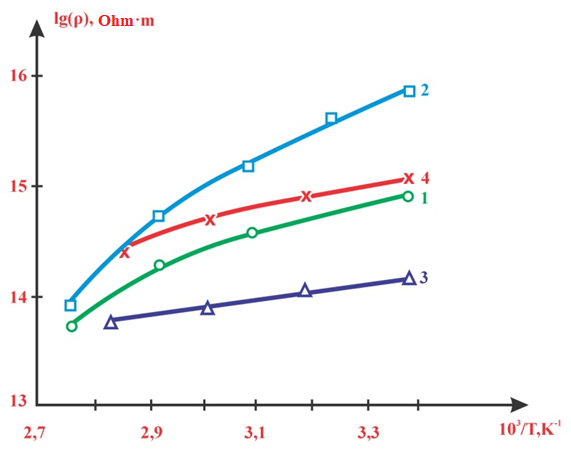
It is known that polymer cooling leads to an increase in electrical strength, but in the temperature range below -2500 C the electrical strength of polyethylene does not change much [4, 5, 6]. Determinations of the value of electrical strength of 100 µm thick NFPC-30 film and 200 µm thick glass fabric C-1189 in liquid nitrogen environment at -1960 C showed that Epr of NFPC-30 is equal to 105±6 kV/mm, and of glass fabric -40±2 kV/mm. In the process of research it was found out that carrying out measurements in accordance with GOST (i.e. in 1 min. after voltage application to the sample) it is possible to calculate values of ρeff, because by this moment the stationary state is not reached yet.

It was found that in this series of experiments at any temperature, the steady state is reached 10 min after applying the voltage, which made it possible to determine the values of ρres. The results of the calculation are presented in Table 1.

**TABLE 1.** Values of ρres and ρeff for 90 µm thick NFPC-30 film

|  |  |  |
| --- | --- | --- |
| T, 0С | ρeff, Ohm⋅m | ρres, Ohm⋅m |
| 23  50  70  90 | 9,17⋅1014  3,41⋅1014  1,83⋅1014  4,55⋅1014 | 7,57⋅1015  1,41⋅1015  4,83⋅1014  5,94⋅1013 |

The obtained temperature dependences are presented in Figure 2 in the coordinate system lgρ = f(1/T) (curves 1 and 2).



**FIGURE 2.** Temperature dependences of ρeff (1,3,4) and ρres (2) of polyethylene composites NFPC-30 (1-3) and NFPC-10 (4), obtained by measuring the charging currents of 90 µm (1,2) and 1 mm (3,4) thick samples at constant temperature

# RESULTS

From the presented results it is clear that measurements on the declining part of the dependence ісh = f(t) give underestimated values of ρ in comparison with the true values obtained on the stationary part.

In order to find out the possibility of carrying out similar measurements on samples of other materials in the form of thicker plates, measurements of charging currents for NFPC-30 and NFPC-10 were carried out. The latter experiments differed from the previous ones only in the thickness of the samples, which was equal to 1 mm.

It was found that the values of ich are much smaller than for the samples with thickness h = 90 µm, so practically at the limit of sensitivity of the measuring equipment it was possible to measure only decreasing parts of the dependence ich = f(t).

The use of samples with thickness h = 1 mm makes it possible to determine only the values of ρeff in 1 min after applying a voltage to the sample.

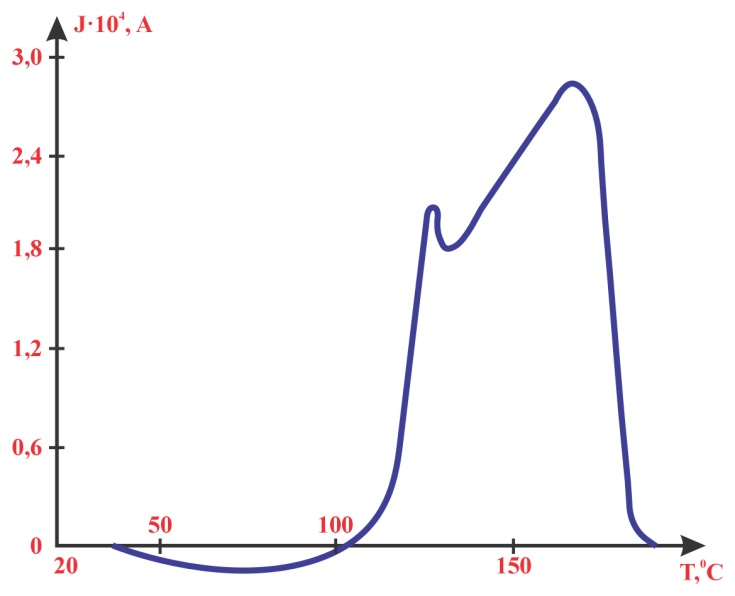
The obtained data are presented in Table 2 and Figure 2 (curves 3 and 4).

**TABLE 2.** Values of ρeff for 1 mm thick NFPC-10 and NFPC-30 specimens

|  |  |  |
| --- | --- | --- |
| T, 0С | ρeff, Ohm⋅m | ρres, Ohm⋅m |
| 25  40  60  80 | 1,0⋅1015  7,5⋅1014  5,0⋅1014  3,5⋅1014 | 1,5⋅1014  1,0⋅1014  7,0⋅1013  6,0⋅1013 |

It is clear from the data obtained that the measurements performed on thicker samples give underestimated values of ρeff compared to the 90 µm thick samples (Fig. 2, curves 1 and 3). Thus, the values of ρost obtained on 90 μm thick film samples should be considered as the true value of ρ (Tab. 1). The dependence ρeff = f(t) for NFPC-10 material (curve 4) shown in Fig. 2 allows us to conclude that an increase in the concentration of additives in the initial material leads to a decrease in the specific volume resistivity ρ. When studying the temperature dependence of ρ of polymer dielectrics, the method of thermostimulated depolarisation currents (TDC) is often used. The essence of the method is as follows: the sample is precharged and placed in a measuring cell, and between the sample and the electrodes insulating pads with ρgas. >> ρsam. The sample is heated at a constant rate and the current flowing in the external circuit is measured.

In the conducted studies, the samples of materials with thickness h = 1 mm were charged in corona discharge, and negative voltage was applied to the high-voltage electrode (needle). A 10 µm thick PTFE (polytetrafluoroethylene) film was used as insulating pads. Figure 3 shows one of the typical TDC curves obtained for the NFPC-30 composite.



**FIGURE 3.** Thermally stimulated depolarization (TDC) current curve for NFPC-30 sample with thickness h = 1 mm

# DISCUSSION

The methods of processing current curves depend on the assumptions about the mechanism of charge relaxation [7, 8, 9]. A formal analysis of TDC maxima can be carried out taking into account a number of assumptions:

- the electret potential difference decreases with time according to the law ve = ve0exp (-t/τ);

- the relaxation time τ depends on the temperature τ = τ0exp(W/kT);

- charge carriers do not pass to the electrode.

The positive maximum on the TDC curve (Fig. 3) is determined by conduction processes, therefore, it was necessary to study this maximum. For this purpose, the entire temperature range of this maximum was divided into equal intervals ΔT = Ti – Ti-1 = 100 C. In this case, the charge was calculated numerically by integrating the TDC current curve.

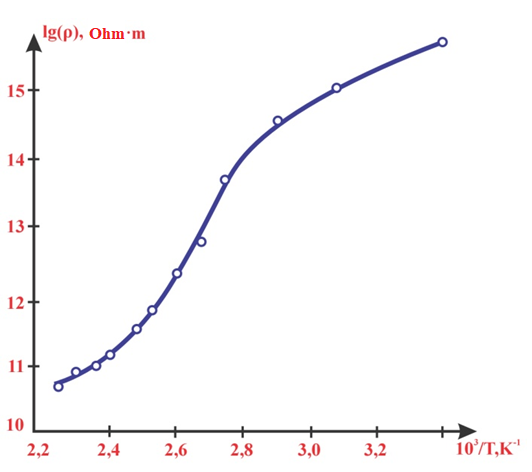
Since the relaxation of the main charge due to conduction takes place at high temperatures (the maximum is in the range 150-160 0C), using the TDC method, we obtained the values of ρ at elevated temperatures. The data are presented in Table 3, from which it can be seen that at high temperatures the values of specific volume resistivity ρv for the investigated materials are close.

**TABLE 3.** Values of ρv calculated from TDC currents

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Material  T, 0С | ρv, Оhm⋅m | | | |
| HPPE | LPPE | NFPC-10 | NFPC-30 |
| 150  140  120 | 9,0⋅1010  1,0⋅1011  5,8⋅1011 | 8,3⋅1010  1,4⋅1011  4,0⋅1011 | 1,2⋅1011  2,0⋅1011  5,4⋅1011 | 9,6⋅1010  1,2⋅1011  6,2⋅1011 |

Thus, as a result of research it is established that the influence of additive concentration on the value of ρv at temperatures lower than 1000 C, the method of TDC does not allow to calculate the values of ρ.

Figure 4 shows the dependence lgρ = f(1/T) for the NFPC-30 composite obtained in the temperature range from 23 to 170 0C. This dependence has a complex curvilinear character, which is consistent with theoretical ideas that at T > Tc (i.e., the highly elastic state of the material), the activation energy decreases with heating, and, therefore, the dependence   
ρ = f(T) cannot be described by the simple relation ρ = ρ0 ЕW/kT with a single activation energy W. This may be due to the increasing mobility of macromolecules and the emergence of a group mechanism of ion motion [10, 11].



**FIGURE 4.** Total dependence of specific electrical resistance on temperature for NFPC-30 composite

Probably, this explains the decrease in the influence of impurities and their concentrations in the investigated materials with increasing temperature. The main results of the study of difficult-to-combust dielectrics at microwave after irradiation of 5 samples for each material are presented in Tables 4-6. In calculating ε/ and tgδ, the mean value of the parameters, standard deviations and σ confidence intervals Δ at the confidence level F = 95% were determined. The measurement error determined by the passport data of the plant is 20% when measuring tgδ and 1.5% when measuring ε/.

As a result of the conducted research, it was found that the introduction of additives providing fire resistance of polyethylene composite leads to an increase in dielectric permittivity and an increase in the dissipation angle tangent of dielectric losses compared to the initial PE. However, in the investigated area of temperatures and frequencies of the electric field, the electrical characteristics of the material remain high enough.

**TABLE 4.** Values tgδ measured at 3.1 GHz

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter Material | tgδ | σtgδ | Δtgδ | σtgδ |
| HPPE (source)  LPPE (source)  NFPC-10  NFPC -20  NFPC -30 | 6,0⋅10-4  2,3⋅10-4  1,2⋅10-3  7,6⋅10-4  8,5⋅10-4 | 2,7⋅10-5  1,7⋅10-6  9,5⋅10-5  1,1⋅10-4  7,4⋅10-5 | 3,3⋅10-5  2,1⋅10-6  1,2⋅10-4  1,4⋅10-4  9,2⋅10-5 | 1,2⋅10-4  4,6⋅10-5  2,4⋅10-4  1,5⋅10-4  1,7⋅10-4 |

**TABLE 5.** ε/ values measured at 3.1 GHz

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter Material | ε/ | σε/ | Δε/ | σε/ |
| HPPE (source)  LPPE (source)  NFPC-10  NFPC -20  NFPC -30 | 2,23  2,25  2,35  2,38  2,45 | 9⋅10-5  1,6⋅10-2  6,5⋅10-3  1,8⋅10-2  4,5⋅10-3 | 0,01  0,02  0,008  0,02  0,006 | 0,03  0,034  0,035  0,036  0,036 |

**TABLE 6.** Measurement results of ε/ and tgδ at 10 GHz

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Nобр. | f0, МHz | Δf, MHz | (1/Q)⋅103 | ε/ | tgδ⋅104 |
| LPPE (source) | | | | | |
| 1  2 | 10240,01  10249,40 | 1,44  1,50 | 1,40  1,46 | 2,05  2,01 | 1,75  3,63 |
| HPPE (source) | | | | | |
| 1 | 9712,01 | 12,50 | 1,90 | 2,13 | 2,26 |
| NFPC -10 | | | | | |
| 1  2 | 10192,93  10192,59 | 2,82  2,79 | 2,77  2,74 | 2,21  2,20 | 1,46  1,43 |
| NFPC -20 | | | | | |
| 1  2 | 10227,30  10222,87 | 2,30  2,31 | 2,25  2,26 | 2,28  2,25 | 1,20  1,18 |
| Glass cloth С-1189 | | | | | |
| 1  2  3 | 10353,12  10371,76  10,365,66 | 2,18  2,52  2,84 | 2,71  2,43  2,74 | 3,27  3,21  3,23 | 40,3  37,90  46,20 |

The value of dielectric losses at a frequency of 1 MHz, according to the standard 16336-87, for fire-resistant composites should not be higher than 3⋅10-3. This value tgδ is much higher than the maximum value of tgδ value, equal to 7⋅10-4, obtained for NFPC-30 composites in the temperature range from -150 to 80 0C.

**CONCLUSION**

It can be seen from the presented data that the scatter of the obtained experimental data (Δtgδ and Δε/) is within the measurement error (δtgδ and δε/). The measurement results indicate that at 3.1 GHz LPPE (source) has lower losses compared to HPPE (source), and the values of ε/ for these materials are almost the same. The addition of filler to LPPE leads to an increase in both measured parameters (tgδ and ε/).

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