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PARTICLE CONCENTRATION IN ELECTROSTATIC OIL CLEANER PROCESS FOR POWER GENERATING EQUIPMENTS

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This paper refers to the issue of impurities separation from dielectric liquids by electrostatic oil cleaner process. An electrofilter and his efficiency is analyzed and the obtained data from modeling and simulations of the electrofiltering process is presented, where mass transport of electrically charged particles in electric field is considered. Together with the obtained numerical results, experimental results are presented to confirme the efficiency of the analyzed electrofilter. Electrofilter capacity to purge dirt particles from dielectric liquids is analyzed, particles whose size varies in large limits from 10^{-9} to10^{-3} m, in this paper being analyzed the concentration of particles and their sedimentation areas.

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1. Introduction

In this paper an electrofilter for dielectric liquids is presented, for which a modeling and simulation and an experimental analysis of the concentration of charged particles and filtration efficiency is made, Fig. 1, [1]. A modeling and simulation was performed on an electrofilter for dielectric liquids, Fig.1, were its filtering efficiency was analyzed in two main stages. In first stage the electrofilter was filled with impure dielectric liquid, while in the second stage the pressure at the inlet was turned off (the electrofilter is filled with suspension), a transient analysis being made were the impurities concentration and its filtration efficiency is analyzed. The model examines the effectiveness of impurities separation under the influence of an electric field. Similar simulations can be found in the documentation of Comsol Multiphysics program, version 3.4 [2], this program being used to conduct the modeling.

In this paper is analyzed an electrofilter of own conception [1], which has the advantage of separating particles whose size can vary in large limits, from nanoscale to microscale. Analyzed electrofilter can be used for cleaning oil in large quantities, but can also be used at reduced size with possible applications in nanotechnology and microtechnology, considering the growing interest of current research in the field of nanoparticles and microparticles manipulating in electric fields.

To determine the cleaning efficiency of analyzed electrofilter, along with experimental methods can be successfully used modeling and simulation methods, with which can be analyzed the electrofilter efficiency. Modeling and simulation is an important process because it provides useful information about the configuration of the electric field, about the distribution of concentration or the particle trajectory inside of the electrofilter.

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2. Physical model

In Fig.1 is presented a schematic diagram representation for the physical model in 2D axial symmetric coordinates. An electrofilter for dielectric liquids is considered [3], Fig.1, consisting in a body (4) in the form of a vertical cylinder which has a height of 0.037 m and 0.1 m in diameter, filled with impure dielectric liquid. The bottom side of electrofilter is the inlet (6) for the impure dielectric liquid and the top is the output (2) for the purged dielectric liquid. The electrofilter body is made of metal and is earthed. Inside to the electrofilter body (4) a centered high potential electrode (7) is placed, this electrode being insulated (1) with insulation which is interrupted by cross-cut slits to create the inhomogeneous electric field. The diameter of central electrode is 0.002 m. Around the central high potential electrode, in the body of the electrofilter and concentric with them, is positioned an intermediate group of 4 similar floating potential electrodes (5), as discs with central circular windows. The central circular windows diameter of these floating potential electrodes is 0.01 m. The external diameter is 0.092 m and their thickness is 0.003 m. The horizontal distance between these electrodes is 0.005 m.

The high potential electrode (7) and the floating potential electrodes (5) are made of copper. The cross-cut slits of high potential electrode are positioned symmetrically between the floating potential electrodes. Inner and outer edges of the floating potential electrodes are insulated with dielectric material. The work fluid is characterized as an oil-particle suspension, liquid with known electrophysical properties. Subjected to an inhomogeneous electric field the dispersed particles will moves.

To achieve the numerical calculus, the geometry is represented in 2D axial symmetric coordinates.

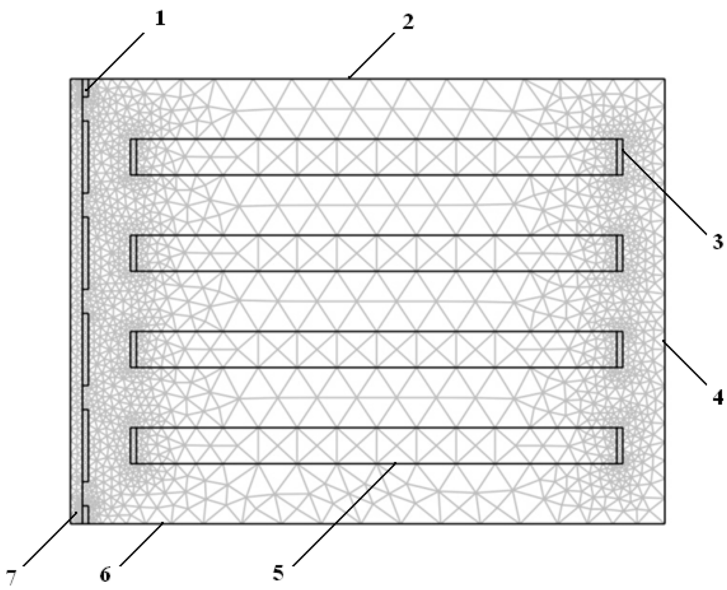

Fig. 1. Principle scheme of electrofilter with four floating potential electrodes, a 2D axial symmetrical section (area of numerical integration of equations (mesh)): 1- insulation, 2 – outlet, 3- insulation, 4 - electrofilter body, 5 - floating potential electrodes, 6 – inlet, 7 - high potential electrode.

This paper aims to determine the concentration of particles and the electrofilter efficiency.

3. Mathematical model

To describe the electrofiltering process of the particles from dielectric liquids and particle concentration distribution inside of the analyzed electrofilter, Comsol Multiphysic modeling and simulation software is used. For fluid flow analysis, Navier-Stokes equations are used, for electric field calculation Laplace equation is used and for determining the concentration of impurities in the fluid Nernst-Planck equations will be used [4].

The analysis is made in two stages, first in stationary mode and second in transient mode. Modeling steps include a stage of filling of the electrofilter with impure dielectric liquid, and the second stage when the convective flow is stopped and a potential difference at the electrodes will create a particle mass flux under the influence of the created electric field. In the second stage the particles will be transported by the electric field lines of forces in the direction of the floating potential electrodes, electrodes on which these particles will sediment. These two stages correspond to the real situation of use of the electrofilter.

As simplifying assumptions, the effect of electric field on the fluid near to the electrodes surface or particles (electro-osmosis) is not considered, and the force of gravity will be zero, g = 0.

The equations that are describing the process can be analyzed separately for the two-stage that are considered in numerical analysis.

In the filling stage, when the electrofilter is filled with impure dielectric liquid without applying at electrodes a potential difference, Navier-Stokes equations are describing the flow of suspension inside of the electrofilter,

$$-\nabla\cdot\eta\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^{T}+\nabla p=0\right)$$
$$\nabla\cdot\mathbf{u}=0$$

where η is dynamic viscosity (kg/(m·s)), $\mathbf{u}$-speed (m/s), p-pressure (Pa).

The impurities present in the dielectric liquids favors an increase of conductivity up to 10^{-8} cm^{-1} MHO. Therefore in first stage of electrofilter filling, the current density in liquid is given by Ohm's law,

$$\mathbf{i}=-k\nabla V$$

where k is the conductivity of liquid (S / m), V is the potential (V). In steady-state the current density equation becomes,

$$\nabla\cdot\mathbf{i}=0$$

resulting,

$$\nabla\cdot(-k\nabla V)=0$$

The flux vector of ions in liquid, is given by Nerst-Planck equation equation,

$$\mathbf{N}_{i}=-D_{i}\nabla c_{i}-z_{i}u_{mi}F_{ci}\nabla V+c_{i}\mathbf{u}$$

From where for mass balance equation at steady state for species *I* results:

$$\nabla(-D_{i}\nabla c_{i}-z_{i}u_{mi}F_{ci}\nabla V+c_{i}\mathbf{u})=0$$

Were c_i is the concentration (mol/m^3), D_i - diffusivity (m^2/s), z_i - charge number, u_{mi} - mobility (s·mol/kg), and *F*- Faraday's constant (C/mol).

For the first stage of filling with impure dielectric liquid the electrofilter, the liquid flow is considered to be laminar at the inlet area of electrofilter and at the electrofilter outlet the pressure is zero.

The boundary conditions for the conservation of mass are given by migration and convection equations, the diffusion is negligible,

$$\mathbf{N}_i \cdot \mathbf{n} = (-z_i u_{mi} F c_i \nabla V + c_i \mathbf{u}) \cdot \mathbf{n}$$

In the second stage of process when the convective flow is stopped and a potential difference at electrodes is applied, new boundary and subdomains conditions for separation stage are set. In this stage of separation, the fluid flow through electrofilter is turned off, and a high voltage is applied at the central electrode, which leads to an electric field between electrodes. The charge-balance equations inside to the electrofilter is solved and the boundary conditions are,

$$\nabla \cdot (-k \nabla V) = 0$$

To solve the problem in transient mode it requires an initial condition for conservation of mass, which is obtained from the solution of the equations solved during the filling.

$$c(t=0) = c_{filling}$$

4. Experimental procedure

An experimental analysis of dielectric particles-transformer oil suspension in static electric field was made using the electrofilter, the scheme which is presented in Fig. 5.

Suspended particles behaviour was observed through a transparent top cover of electrofilter, Fig.6, samples for analysis of investigated suspensions being taken from the outlet from the top of the electrofilter, Fig.6.

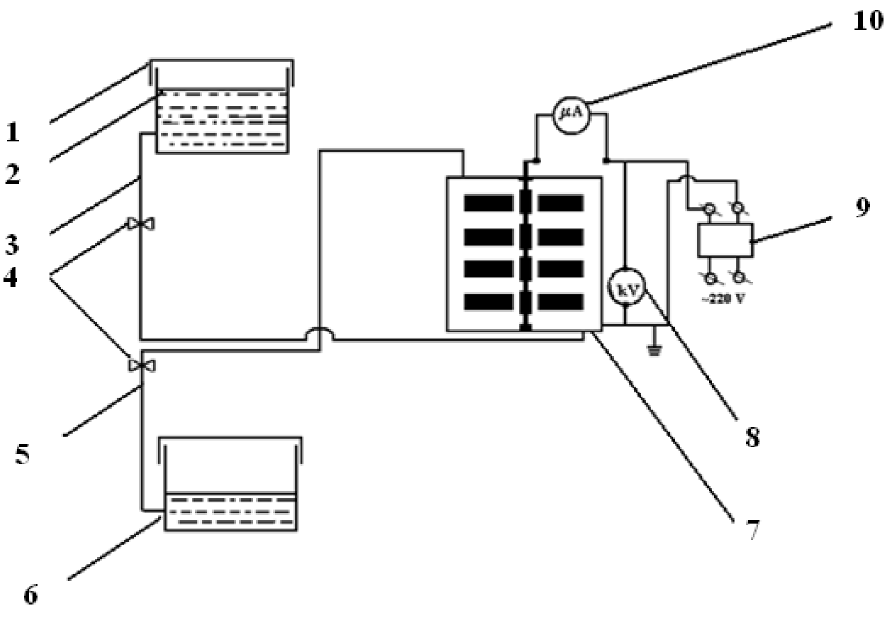

Fig. 2. Experimental installation scheme for the experimental study of electrofiltering process of a dielectric liquid in an electrical field: 1- impure dielectric liquid reservoir; 2- transformer oil; 3,5- pipes; 4 – valves; 6- filtered dielectric liquid tank; 7- inlet for impure oil; 8- kilovoltmeter; 9- DC source; 10- microampermeter.

A suspension of dielectric particles-transformer oil, with burned paper particles was prepared. This tipe of impurities were selected to simulate the actual conditions of using for transformer oils where the insulation paper degrades over time leading to degradation of the electrophysical properties of oil.

With a scales Mettler Toledo, AG 204 was measured the amount of particles n_0 and was prepared a suspension of burned paper (ash) -transformer oil at a rate of 1.5g ash to 500 ml transformer oil. Ash particles size varies very large, the experiment seeking the behavior of all particles, regardless of their size. The suspension has been undergoing to a ultrasonic device, type Fisherband FB1105, for homogenization at 140KHz for a period of 15 minutes. The electrofilter was connected to a adjustable DC power supply, ИВН-50/ 0-30 KV. Residual impurity concentration was measured using a spectrophotometer Perkin Elmer, STD Detector Module. The concentration was determined measuring the absorption and comparing the results with analytical results of similar suspensions in which the concentration of impurities was known.

The first step of experiments was achieved in stationary mode, where the fluid flow is zero, from electrofilter being extracted samples for analysis every 5 minutes. The central electrode voltage was varied between 0-15 KV's and samples were taken at values of voltage of 5 KV, 10 KV, 13KV and 15KV.

Table 1Measured quantities and calculated quantities and their errors.

Nr. crt	Measured size	Numerical value	Measurement device, absolute error	The relative error, %
1.	n_0 - Concentrations of impurities in the liquid in the initial moment of time (t=0)	(0.003) [m^{-3}];	Balance-METTLER TOLEDO, AG 204 $\pm$ 0,2	1,4
2.	n - Concentrations of impurities in the liquid in the actual moment of time (t=0)	$(0.003 - 0.1 \cdot 10^{-10})$ [m^{-3}];	Spectrofotometer Perkin Elmer, STD Detector Module $\pm$ 0,01	$0.08 \cdot 10^{-10} - 2{,}6$
3.	T-time	0-2400 [s]	Cronometer tip COCпр-26-2-010, $\pm$ (1,8…0,6) s	0,05-0,10
4.	I- Electric current intensity	(0-1.2) [μA]	Digital multimeter Agilent, $\pm$ 0,01 μA	2,50-0,03
5.	φ -Voltage	(0-17) [KV]	Digital multimeter Agilent $\pm$ 1 V	0,91-0,45

In Table 1 are presented the measurement devices used for experiments with their error.

5. Results and discussion

Analysis of electrofilter efficiency

This model examines the electrofiltering processs of impurities from dielectric liquids in two stages. The impurities will sediment in the electrofilter electrodes zone under the influence of the electric field lines of force.

In Fig. 2 is represented the steady-state concentration of particles, for the stage of sedimentation. It can be observed how the particles are settling on the floating potential electrodes of the electrofilter and the sedimentation zone of particles in the floating potential electrodes zone.

Similar simulations can be found in Comsol Multiphysics program documentation, version 3.4 [4], this paper taking as modeling and simulation methodology the presented work mentioned above, with necessary adaptations for analyzed electrofilter.

The simulations comprise two main stages. In first stage the electrofilter was filled with impure dielectric liquid, while in the second stage the pressure at the inlet was set to zero, p = 0, and a transient analysis is performed to determine the concentration of impurities inside to electrofilter, and his efficiency is analyzed.

Particle concentration is represented after 60 minutes in Fig.2, time when the process will reaches steady-state. It can be observed how on the floating potential electrodes zone the particles will settle and the sedimentation zone between these electrodes.

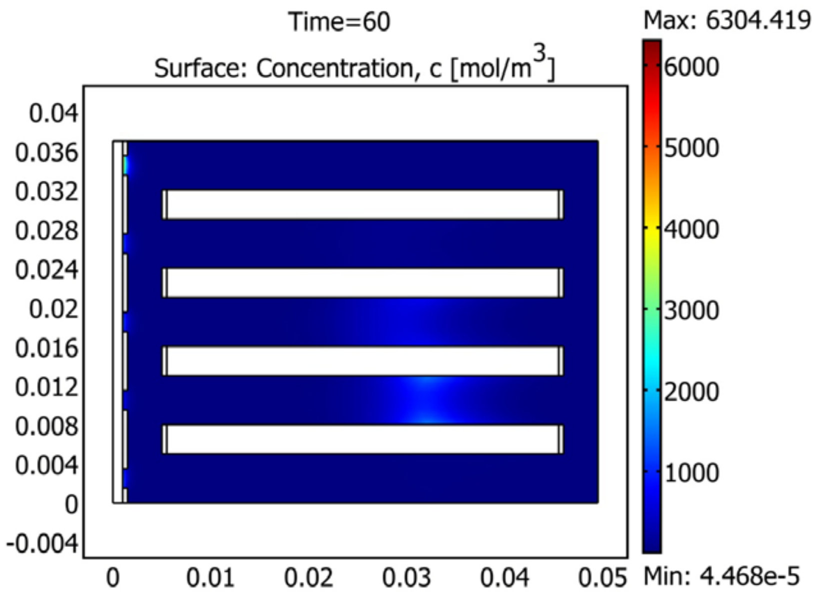

Fig. 3. The steady-state concentration distribution during the electroseparation stage.

The areas of maximum concentration is between the electrodes with floating potential. The particles will migrate between the electrodes with floating potential under the influence of the electric field lines of force. Particle concentration is high at the central electrode of the electrofilter, where the electric field magnitude is high.

In Fig.3 can be observed the concentration distribution between the electrodes of the electrofilter and areas of maximum and minimum for particle concentration distribution.

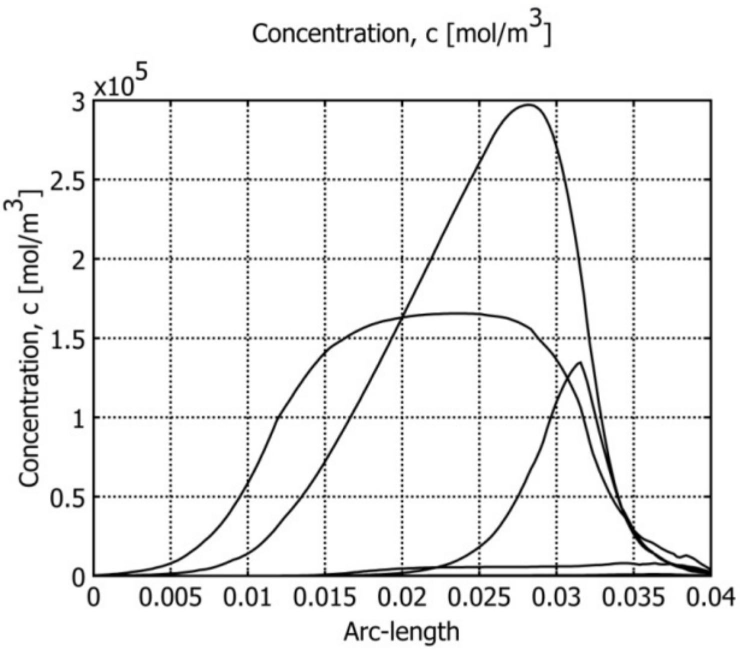

Fig.4. Particle concentration distribution between the floating potential electrodes from Fig.2. The origin of x-axis marks the starting point of the horizontal line parallel to the floating potential electrodes and positioned at midway distance between two neighboring floating potential electrodes.

Looking at Fig. 2 and Fig. 3, it is found that the particles concentration is high in the floating potential electrodes zone. To determine the effectiveness of filtering process is necessary to measure the particle concentration at the outlet of electrofilter. The dependence of particles concentration at electrofilter outlet is represented in Fig.4.

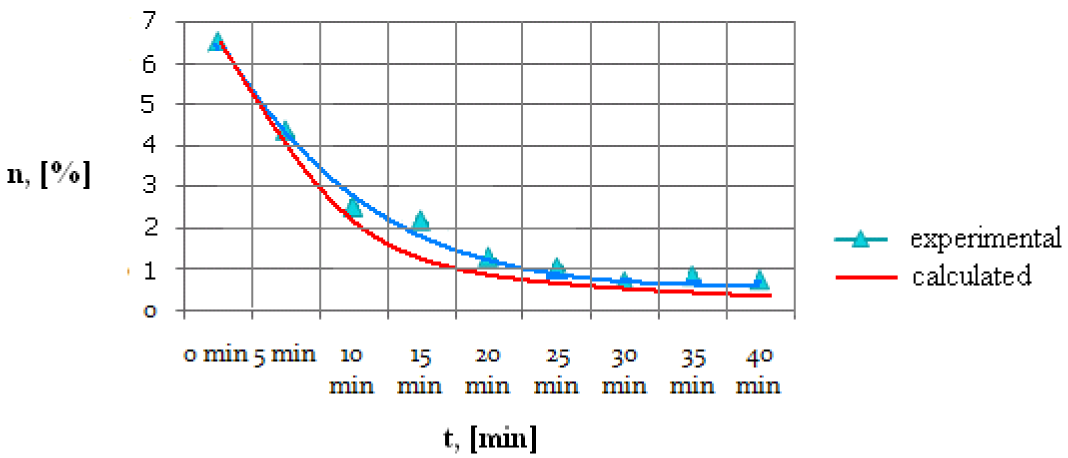

Fig.4. Particle remanent concentration dependence at electrofilter outlet in minutes, n(t).
φ = 4KV, inlet concentration n_0 =0.003[%].

Looking at Fig.4, can be observed that the dependence of particles concentration at electrofilter outlet will decrease rapidly. It can be seen from Fig.4. how the cleaning process of the particles occurs in the first 25 minutes, after this time is reaching a steady-state and much of the impurities presented in oil are settling in this time.

Analysis of dielectric particles-transformer oil suspension

In first step was determined the influence of voltage on the process and especially the dependence of efficiency of the electrofilter n/n_0 from the applied voltage in time t, the mass flux of particles and the influence of other parameters that influence the proces.

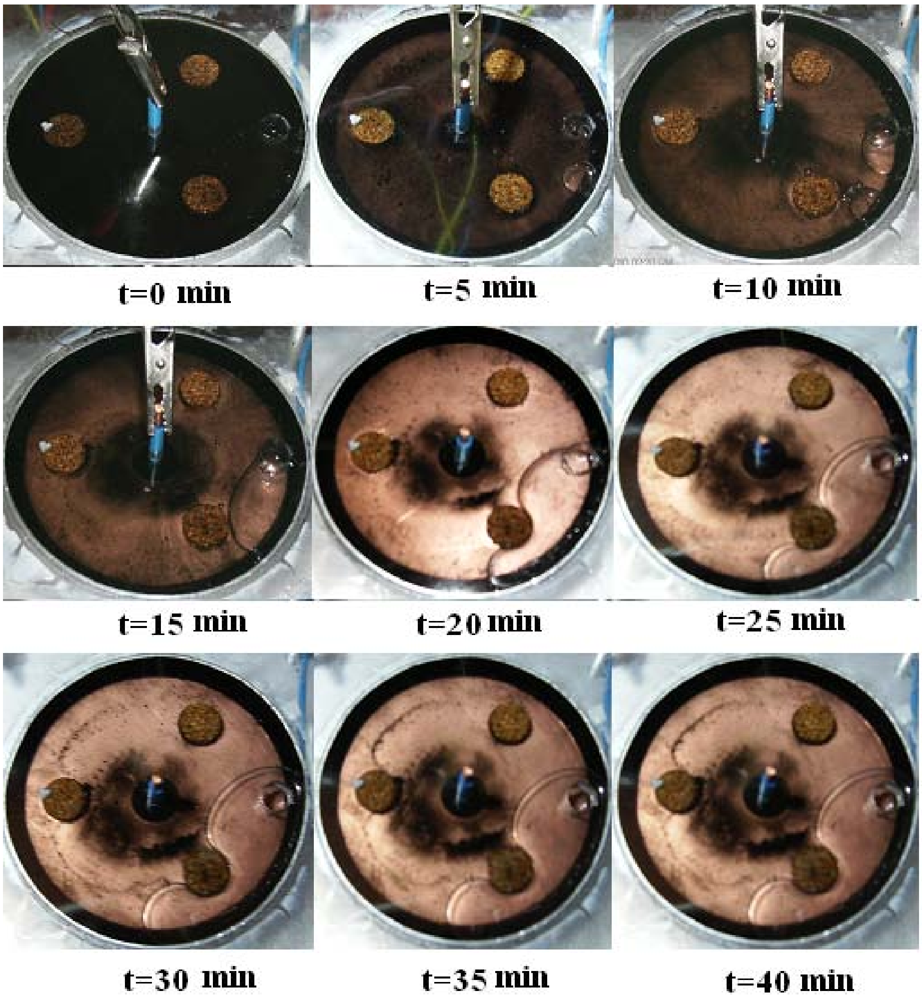

Fig. 6. Electrofilter for dielectric liquids filled with a burned paper-transformer oil suspension. Photos taken at an interval of five minutes, the voltage applied to the central electrode, φ = 10 KV.

In the analysis of the concentration of impurities in suspension, it is known that the dependence of residual impurities n to the initial concentration n_0 can be exponentially or relaxed [5].

$$n(t) = n_0 \cdot e^{-t/\tau}$$

where τ is the characteristic relaxation time, which depends on factors that influence the electrofiltering process.

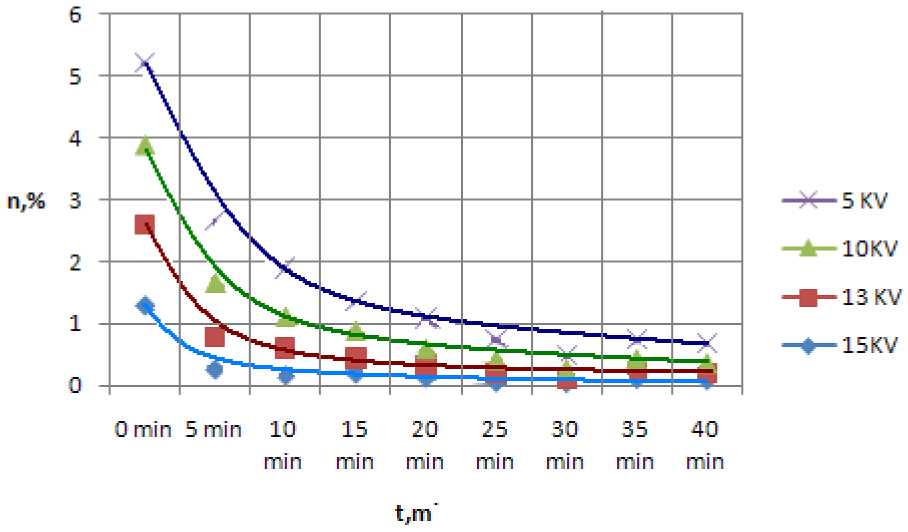

Fig. 7. Residual impurity concentration dependence versus time for different voltages φ.

The graphs presented in Fig. 7 represents the typical experimental dependence of residual concentration n from the applied voltage to the central electrode, for different voltages. Analyzing the obtained data, we can see that the cleaning of the fluid increases with the applied voltage to the central electrode.

Dependences of concentration n in Fig.7 demonstrates that there is a critical point in the process of oil purification from were the oil purification process ceases.

There is a critical time t_c that increases with voltage, while the minimum residual concentration decreases with voltage.

The mass flux of impurities to the center of the electrofilter can be observed in pictures from

Fig. 6. Dielectric particles are attracted to the central electrode an then to the floating potential electrodes and are captured on the surface of these electrodes or in the zone between them. The particles gets crowded in the center of the electrofilter. Particle agglomeration in that area is influenced by the polarity and the inhomogenity of the electric field, the permittivity of phases that make the suspension, and by the electric charge of particles. Particles trajectory is influenced by the electrostatic forces acting on them [5].

$$F = \begin{cases} q\overline{E}, (\overline{p} = 0, q \neq 0), \\ (\overline{p}\nabla)\overline{E}, (\overline{q} = 0, p \neq 0), \\ q\overline{E} + (\overline{p}\nabla)\overline{E}, (\overline{q} \neq 0, p \neq 0). \end{cases} \tag{1}$$

If we adopt in the first phase of analysis as simplifying assumption that particles are not electrical charged, then the direction of movement of particles in the area where the electric field intensity is greater can be explained relatively simply. Knowing that the electrostatic force acting in this case on the particle is the dielectrophoretic force, the direction of movement of particles is given by the Clausius-Mossotti factor which, depending on the permittivity of the phases, explains the trajectory of movement for particles,

$$K = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}$$

Since particles are moving to the central electrode in areas where the electric field intensity is at maximum level, the electrostatic force acting on the particles is known as positive dielectrophoresis, particles moving in that area because the particle permittivity is smaller than transformer oil permitivity. In reality, in most cases, the electric charge of particles is not zero, so the force that express the trajectory of movement of particles is given by the last equation from the formula 1.

Effect of impurities concentration

If the initial concentration of impurities n_0 in suspension increase, the efficiency of electrofiltering process decreases in direct proportion with the increase of impurities.

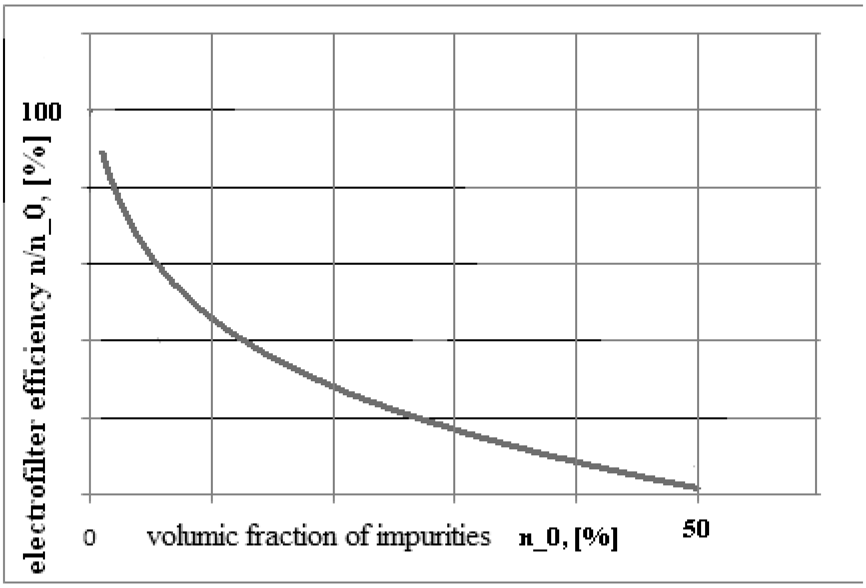

Fig. 8. Effect of initial concentration of impuritieson the efficiency of the electrofilter. Increasing the concentration of impurities in solution with a volume fraction up to 50%, caused a considerable decrease in filtration efficiency.

Effect of electrode polarity

Analysis of equation1 shows that in an electrofilter for dielectric liquids, the electrostatic forces can act differently, and there are forces that occur when are charged particles, forces on particles in an inhomogeneous electric field on an induced dipol, or both. Generally the electrophoretic force on charged particles in inhomogeneous electric field is greater than the dielectrophoretic force.

If a dielectric particles-dielectric liquid suspension is considered, the electrophoretic and dielectrophoretic effects are visible in different phases of electrofiltering process.

In first minutes of electrofiltering process reveals that the main phenomena that govern the process is the dielectrophoresis, this being due to the fact that the dielectric particles are not charged with an electric charge.

Under the effect of the dielectrophoretic force, particles with lower dielectric permittivity than the dielectric fluid that constitutes the continuous phase are attracted to the area where the electric field intensity is high, in the transversal slits of central electrode, as can be seen from Fig. 6.

It is obvious that in the first few minutes when the process takes place, the dielectrophoretic force is greater than the electrophoretic force on particles. This is because the dielectric particles are not yet loaded with an excess electric charge.

Near the central electrode, the dielectric particles can be charged with an electric charge through various mechanisms of electrization, in this case the electrophoretic force on particles having a more significant impact on particle trajectory.

Changing the polarity at the electrode does not produce a significant change in the filtration efficiency, or in the behavior of particles, particles are still attracted to the center of the electrofilter, meaning that the main force acting on the dielectric particles until the particles will reach the central area of the electrofilter is the dielectrophoretic force.

Table 2. Effect of electrode polarity on electrofiltering process, test duration t = 40 min.

Voltage, $\varphi,[KV]$.	Remanent concentration $n,\%$, Central electrode is positive (experimental data)	Remanent concentration $n,\%$, Central electrode is positive (calculated data)	Remanent concentration $n,\%$, central electrode is negative (experimental data)	Remanent concentration $n,\%$, Central electrode is positive (calculated data)
5.5	20.4	21.3	19.6	20.1
4	70.1	70.5	69.4	70.3
2	82.2	85	80.6	84.3
0.5	83.8	86.1	83.5	87.9

Current-voltage characteristics

Current-voltage characteristics in different phases of electrofiltering process provides data for understanding the changing in the intensity of the electric current in the circuit at different voltages applied to the central electrode of the electrofilter.

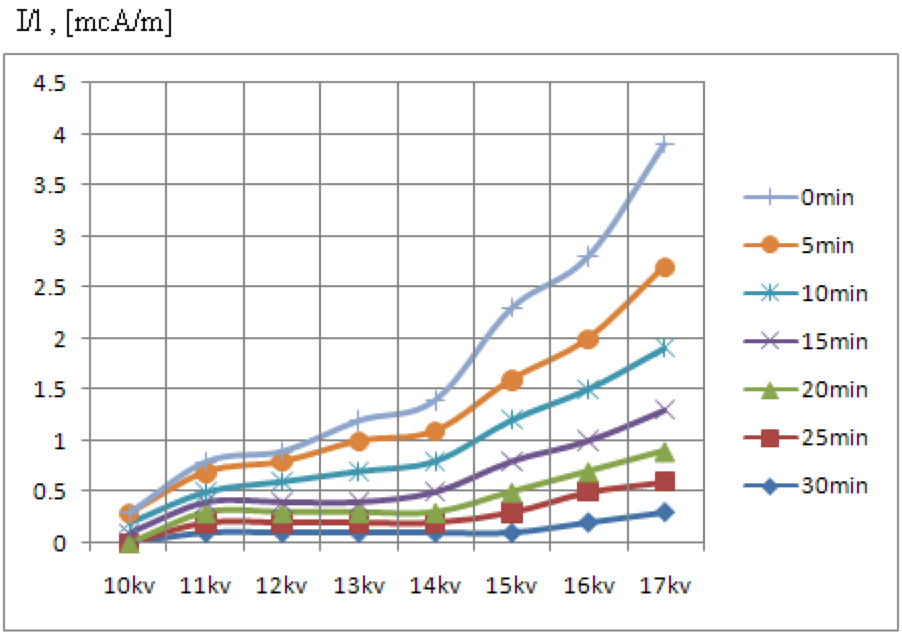

Fig. 9. Current-voltage characteristics for dielectric particle-transformer oil suspension.

Electric current intensity increases with increasing of the initial concentration n_0 of impurities in suspension, and will also increase with increasing the size of the particle. Increased intensity of electric current in circuit driven by the concentration of impurities or by the suspended particle size favors the electrification of dielectric particles suspended in the liquid.

From Fig. 6 we can see significant changes and improvement of electrical properties of the oil after 30 minutes, subjected to different electrical voltages.

6. Conclusions

This paper proves the utility of modeling programs in the analysis of filtering efficiency of electrofilters for dielectric fluids.

Was made a modeling and simulation of the electrofiltering process for an electrofilter of own conception and was analyzed the concentration of impurities and the efficiency of the electrofilter.

The obtained numerical results were compared with experimental results. Comparing the obtained numerical results with the experimental results, similar data were obtained in terms of concentration of residual particles.

Residual concentration decreases with increasing of applied voltage, with processing time and initial volume fraction, and is 1-4% higher if the central electrode polarity is positive than when the polarity is negative.

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