Engineering Electret Materials

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The applications of the electret effect in manufacturing and utilization of engineering materials are reviewed.

INTRODUCTION

The Electret state of materials has been so far insufficiently investigated. However, the application of the electret effect in manufacturing and utilization of engineering materials permits us to solve many technical problems (Fig. 1). Therfore, we will review the principles of engineering electret materials (EEM) development, and analyze the advantages of the electret effect in machine-building and other industrial applications of electrets.

RESULTS AND DISCUSSION

The problems solved by analyzing the electret state of engineering material components could be divided into technological and operational.

1. Technological Decisions

The majority of EEM are composite materials whose manufacturing process has been previously developed for polymeric composites. Therefore,
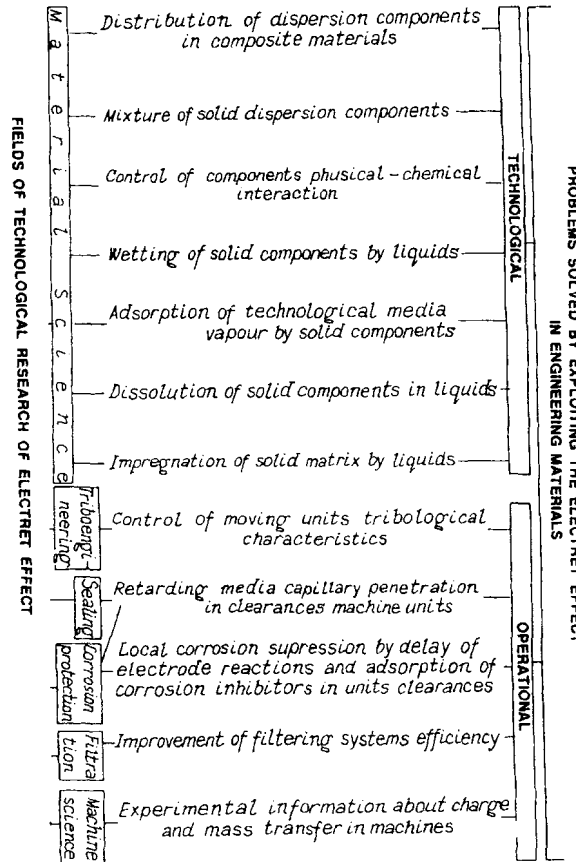
FIGURE 1   Electret effect utilization in machine-building engineering materials.

many of the polymer systems discussed below belong to this class of materials.

The dispersed solid particles distribution in the composite material bulk could be easily controlled by using the effect of electric fields on dispersed particles and other material components.

The data in Table I show the effects of corona discharge action on the fluidized polymer powder deposition. It is obvious, that the field voltage results in a reduction of the electrically deposited layer integral charge, and in a nonmonotonic variation of its thickness, deposition rate and other parameters [1].

Interaction between the composite components electric fields allows for mass transfer control during articles production. This is realized in the

TABLE I

Characteristics of fluorplastic-3 powder layer deposited onto grounded metallic plates related to a permanent-intensity electric field supplied to particles

Parameters	External field intensity, kV/m				
	75	150	250	350	500
Specific charge, 10^{-4} C/kg	4.2	2.7	2.2	1.6	1.3
Limiting layer thickness, um	115	305	460	825	515
Degree of thickness evenness (scatter across thickness)	9	8	9	4	13
Maximum rate of deposition, 10^{-2} kg/ (m2 c)	0.7	1.7	2.5	2.2	0.7

process of the polymer powder binder electrical deposition on the reinforcing elements of composite materials (gauze, fabric, foil, etc.) when fabricating prepregs [2]. Prepregs are semi-products of polymer composites used in large-sized articles production. Using a high-voltage and grounded electrodes (Fig. 2) a two-sided deposition is carried out with similar charged particles is carried out (a), with the conducting fillers which are oppositely charged and dielectric ones (b), with fine materials (less than 0.5 mm) the polymer binder particles are deposited from one side (c).

Electret state of components is utilized in a number of branches to solve versatile technological problems related to governing componential distribution in composites. An original technique has been developed in the textile materials science [3] aimed at production of napped materials. A fleeced nap is electrostatically charged and supplied into inhomogeneous field on a vibrating disc. The hairs are attracted to the disc disposing vertically by their ends. Under the action of inhomogeneous field they move in such position from the disc center to its periphery along spiral trajectories. The longer and thicker is the hair, the larger is the trajectory and the faster the motion. The hairs with greater dielectric permeability obtain higher velocity. Thus, separation of hairs is performed by the criteria of electrical and geometrical properties using diffferent batches of nap sticking to the substrate according to an assigned pattern.

Abrasive particles glued to a base during emery paper production are of irregular angular configuration. One of their angles is more acute. When conventionally distributing the particles over the base by screening or spraying, the angular effect is not taken into consideration. The dielectric abrasive particles are, however, due to electric fields oriented and glued in such a way that their acute angles are directed upwards.
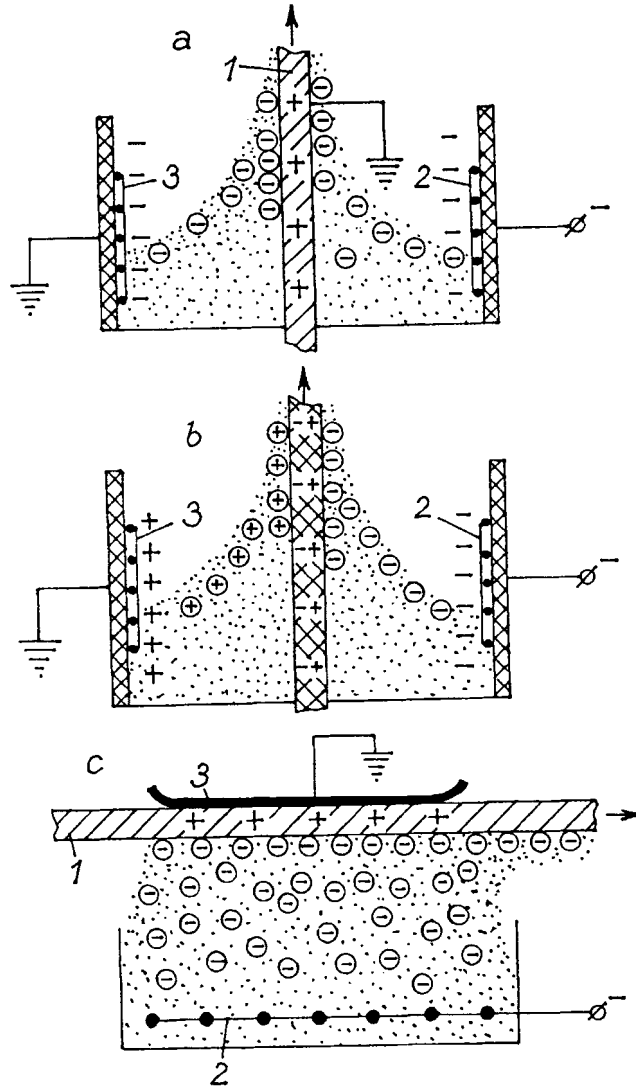
FIGURE 2   Scheme of powder polymer binder electrical deposition on flat reinforcing fillers.
a, b-bilateral deposition, c-on one filler side. 1-filler, 2, 3-elements of electret system.

One more example is a flexible roofing and waterproofing material. It is
produced by saturating cardboard made of wooden or textile fibers with oil
bitumen with subsequent protective sprinkling with asbestos, talc, etc. The
fibrous raw material is fed from a hopper onto conveyer belt and is caught
under electrodes powered by pulse current. The light fiber fraction is trans-

ported by the air flow to the interelectrode space of the forming device. The fibers charged by the corona electrodes stick to conveyer belt energized by another pole of d.c. source. One layer of the fibers lies down lengthwise and the other crosswise to the belt. This is achieved by two pairs of accessory electrodes. One pair creates the field whose force lines are directed along- and the other across-the belt. So, the fibers are oriented in two directions. The cardboard is formed and simultaneously saturated with bitumen using electric pulverizer. The blank is compacted by rollers and is sprinkled. The finished product is reeled into rolls and cut [3].

Mixing of dispersed solid composite components is monitored using the method of particle electrization accompanied by their charge value control. This problem is complicated because the components density and dispersion state are inhomogeneous, and their electric properties are different, etc. Nevertheless, convergence of components into stable composite agglomerates is possible when using uncommon technological methods of electrical mixing. The agglomerates formation peculiarities could be attributed to the components donor-acceptor properties at contact interaction during fluidizing [1].

In the 80-s Armenia (SPA "Armselkhozmekhanika") practically inertialess electric mixers were designed which could instantaneously feed components of hundredth gram fractions into the flow mixture, while the mixer productivity was up to 10 kg/h.

Physico-chemical interaction between composite material components could also be regulated by electrization. This is demonstrated by the change in the binder structure at the boundary with the filler. An increase in the polymer temperature of glassification (T_g) has been recorded [1] in the metal-polymer adhesive junction in response to a higher charge of electrically deposited layer. T_g dependence on the fibrous filler (glass, organic fibers) content in the binder differs markedly between the adhesive bonds formed from electrically charged and non-charged polymer particles.

Table II illustrates increase of carbon fiber adhesion to polymer binders for electrically charged polymer particles applied onto fibers in electric field. Adhesion has been estimated by the fiber shear force relative polymer matrix. Adhesion enhancement results from the gain in orientation, polarization and rheological processes in the adhesive contact zone under the action of electric field [1].

The wetting of solid components by liquids depends on the charge value of solid components.

Pentaplast films were hot-molded followed by transfer into the electret state. Corona electrets were obtained by treating of films with corona dis-

TABLE II

Adhesive strength of a carbon fiber and thermoplastics junction

Thermo-Plastic	Forming regime			Adhesive strength, MPa
	$T, °C$	t, min	electric field	
PC	275	15	no	59.4
			Yes	78.4
PEVP	200	15	no	14.3
			Yes	21.0
PTP	225	15	no	24.6
			Yes	29.2

charge. Thermoelectrets were produced from films by an hour-heating at $T = 423$ K under d.c. of $E = 10^{-4} - 10^{-6}$ V/m voltage. The field was withdrawn after the films were cooling to their solidification. The spreading of model viscous liquid diethyleneglycol (DEG) over the films surfaces and equilibrium edge wetting angles were determined using an optic microscope having goniometrical scale with X 200 magnification. A DEG droplet of a 5×10^{-5} m³ volume was placed on the film surface with the help of syringe. The electret film surface charges were measured by way of the compensation contactless method [4].

Table III cites the data on DEG spreading over a positively charged polymer electret film. It is obvious that increase of the electret charge surface density σ, with all other factors being equal, is accompanied by a reduction of DEG initial velocity spread. Simultaneously, the equilibrium edge angle of wetting increases. With growing σ of thermoelectret from 10^{-6} to 10^{-5} C/m², the value of $\cos\theta$ is reduced from 0.45 to 0.25. Electrization is, probably, leading to variations in submolecular structure of the film surface layer. Physico-mechanical properties of the contacting DEG droplet changes under the electret field as well. An additional energy barrier is thus formed against realization of the spreading mobile force.

Adsorption of technological media vapors (solvents, plasticizers, stabilizers, etc.) by solid components is used in a number of techniques for achieving composite materials.

Hereinbelow (par. 4.2), the effect of polymer films electret state is described on kinetics of corrosion inhibitors sorption. This serves a prerequisite for working out electrical methods of a regulated merging solid and

TABLE III

Initial velocities (v) of DEG spreading over penta-
plastic film surface depending on its surface charge
density (σ)

Type fo specimen	$\sigma, C/m^2$	$v, 10^{-4} mm/c$
Reference	0	2.8
Thermolectret	5×10^{-3}	0.6
	3×10^{-3}	0.4
Corona	0.36	0.4

vapor components of composite materials. Regretfully, this perspective di-
rection in materials science is not studied sufficiently.

Solubility of solid components in technological liquids is not a well de-
fined parameter. It was observed already in the 60-s that the electric field
between ion crystal and polar liquid effects the velocity of the crystal sol-
ution [5]. Later, the representation was adapted for solution of electrets [6].
The present authors have presented the possibility of controlling techno-
logical parameters with engineering aspects of polymers solubility [7].

Polymer films were treated with corona discharge (U = 15 kV) to form a
bipolar symmetric charge controlled by contactless compensation method.
The films were then immersed into solvents and the swelling of samples
$H = (m_{sw} - m_{dr})$ and the quantity of dissolved polymer, $p = (m_0 - m_{dr})/m_0$,
were recorded. Here m_0, m_{sw}, and m_{dr} are, correspondingly, mass of the
original, swelled and dried samples.

Figure 3 shows kinetic dependences of the parameters for samples with
different electret charges. The parameter analysis has disclosed that the
regularities of polar ion crystals dissolution [6] are true for noncrystalline
PVB and weakly crystallizing PVC. The PVB dielectric permeability is
$\varepsilon_s = 3.3$, while for its solvent $\varepsilon_1 = 25.1$, i.e. $\varepsilon_s < \varepsilon_1$. Retardation of polarized
solids dissolution is characteristic for such relation of dielectric permeabil-
ity. This regularity is shown in Figure 3a. The curves are going downwards
with increasing polarized charge. With film treatment time t = 2 min. (curves
2 and 2') the mean value of the effective charge surface density is
$\sigma = + - 10^{-8} C/cm^2$, at t = 20 min (curves 3 and 3') $\sigma = + - 2.4 \times 10^{-8}$
C/cm^2. The variation of samples mass on swelling correlates with the poly-
mer mass growth in its alcohol solution. The variation of quantitative
characteristics of swelling under polarization are one and a half to two
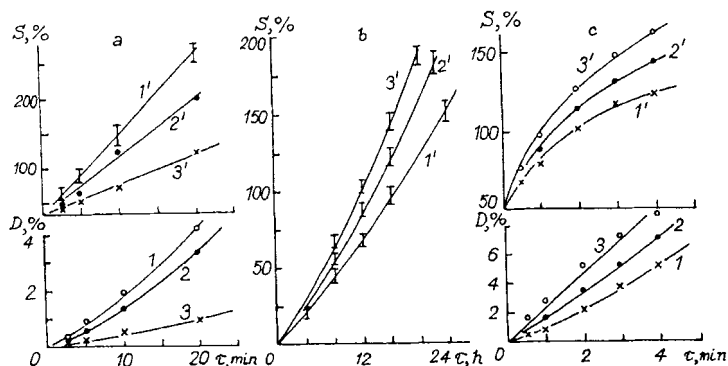orders of magnitude higher than those for dissolution. Dielectric permeabil-

FIGURE 3   Kinetics of swelling (H, 1'–3') and dissolving (P, 1–3) polymer films in low-molecular liquids under various regimes of electric polarization. a-PVB in ethyl alcohol, b-PVC in dioxane, c-PA in HCOOH. Time of film treatment with corona discharge: 1, 1' –0; 2, 2'–2 min.; 3, 3'–20 min.

ity of the weakly crystallizing PVC is $\varepsilon_s = 3.24$, that of its solvent (1.4 dioxane) $\varepsilon_1 = 2.2$, i.e. $\varepsilon_s > \varepsilon_1$. Such relation of dielectric constants determines acceleration of the polarized substance dissolution. Figure 3 does not present diagrams of the solution concentration change for the PVC-dioxane system. The m_{dr} mass of the swelled and afterwards dried PVC specimen appeared to be larger than that of the original m_0. Consequently it was impossible to estimate polymer content in solution by variation of the specimen mass. This can be attributed to phase separation of the system components during swelling, as well as to the formation of gels preventing complete dioxane removal from the PVC matrix during drying. Nevertheless, layout of curves in Figure 3.3, b gives a real picture of correlation between PVC kinetics of dissolution in dioxane and regularities discussed in [6].

Figure 3, c shows the kinetic curves of PA swelling and dissolution in formic acid. When dielectric permeability values of highly crystalline PA are: $\varepsilon_s = 4.3$ and HCOOH $\varepsilon_1 = 57.9$, then $\varepsilon_s < \varepsilon_1$ condition is preserved, under which polarization should promote retardation of solid dielectric dissolving. Since the PA solubility in HCOOH is considerably higher than that of PVB in alcohol, it is anticipated [6] that the retardation effect on polarized PA dissolving is to be lower than on PVB. The position of curves in Figure 3.3 demonstrates, however, that under the influence induced by electric polarization PA dissolving in HCOOH is accelerated. This unexpected result reflects the action of some new factors. PA is known to chemically interact with formic acid. Electrical polarization of specimens is, probably, an intensifying factor of chemical reactions between the polymer and solvent, which

in turn accelerates the diffusion stages of PA solution. Thus, the general law typical of polar solids dissolving is complicated under polymer and solvent reaction by polarization effect on chemical reactions kinetics.

From the above example it follows, that the rate of solid organic polymers solution in low-molecular liquids depends on the polarization charge of the dissolving specimen and the ratio between dielectric permeability of both polymer and liquid. In case the dissolving is accompanied by the components chemical interaction, the process kinetics is influenced by polarization, which can lead to diffusion acceleration of polymer solution. Electric polarization effect on polymer swelling is of great importance for technological modification and processing of composite materials.

The impregnation of composite matrix with liquid binders is one of the most least productive processes. The improvement of this process productivity represents an urgent unsolved problem in materials science technology.

Beginning with the end of the last century the investigations in this field have shown that practically all liquids respond somehow to the action of electric field [8]. It was found that polar liquids viscosity grows with increasing voltage proportionally to square voltage at first and then approaches some stationary value. The limiting viscosity magnitude at which it becomes independent of voltage is called saturation viscosity. Its value depends on liquid conductivity.

In a number of cases the saturation is accomplished with the help of suspension binders. The presence of electrical charges on particles in suspension imposes additional energy limitations on particle distribution and hydrodynamic parameters of suspensions. Such suspensions do not obey the Einstein law and their viscosity under shear flow increases by a value called the electrostatic constituent of viscosity. The phenomenon of viscosity rise is called electroviscous effect [8]. Three electroviscous effects could be discriminated. The first proceeds in dilute suspensions where the interaction between double electric layers of the neighboring particles is absent. The second electroviscous effect occurs in concentrated suspensions where overlapping of the double layers takes place. The third one is characteristic of polyelectrolites solutions and is stipulated by variations of macromolecules shape.

The above data show that the impregnation of the composite material matrix with liquid binders could be controlled by a directed change of its components charge state. Still, acceleration of saturation could not be reached by a simple field application, it needs a special treatment and ingenious technological steps. Therefore, it is not surprising that there are no reports of the matrix impregnation technique in handbooks on compos-

ite materials [9, 10]. This important field of composites technology there-fore, requires further investigation.

2. Operation Problems

Technological use of engineering electret materials permits us to take new approaches for improving the performance of machines and equipment.

The control of frictional characteristics in movable joints is an important tribological problem aimed at energy-, labor- and material saving.

One of its solution consists in preventing the removal of lubricant from the spaces between the microasperities on the wear surface areas under maximum contact stresses. Magnetic lubricating systems and induction sea-lings can serve as examples of the most efficient application of magnetic and electromagnetic fields in solving the problem. In the first case the magnetic field entraps solid lubricants possessing magnetic properties [11] or mag-netic liquids [12] in friction joints clearances. In the second case the elec-tromagnetic field concentrates the liquid metal layer (mercury, gallium, bis-muth, etc.) in the shaft-bearing clearance in the zone of the highest field intensity and the layer is not removed from the clearance [13].

A similar result could be obtained by using electret materials in friction joints. The mechanism of controlling the adhesion of lubricant to the fric-tion pair walls with the help of electret field consists in the following. The dielectric lubricating fluids are subjected to electrization during friction [14]. In case the clearance walls are oppositely charged, the lubricant ad-hesion increases owing to electrostatic attraction (Fig. 4). The polarizing charge is induced onto a dual electric layer of the lubricating interlayer contacting the electret even in the absence of triboelectrization. The con-temporary physico-mathematical models of wetting and spreading take into account the phenomenon and its dependence on a solid body charge [15].

Theoretical predictions indicate that the electrets are useful in triboen-gineering on exploiting the electroviscous-rheological effect, i.e. the fast re-versible rise of effective viscosity in non-aqueous dispersed systems under strong electric fields [8]. The essence of such original structures as clutches, brakes and other frictional devices is in regulation of slippage between two conjugated parts (driving and driven, moving and stationary) aimed at automatic velocity control. A prerequisite of such systems is electroviscous-rheological suspension placed in the friction pair clearance. It is composed of nonpolar liquid (petrolatum, vegetable oil, transformer oil, aromatic hy-drocarbons, amines, etc.) and a solid dispersed phase with a fairly high dielectric permeability (silica of different modifications, metal oxides,
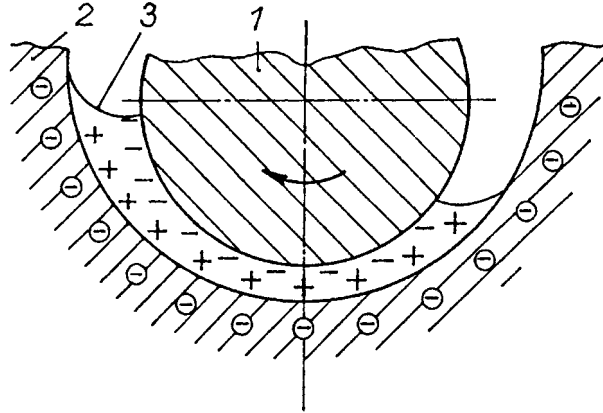
FIGURE 4   Electrostatic interaction between dielectric lubricant and electret support of friction pair. 1-shaft; 2-bearing; 3-lubricant interlayer.

aluminosilicates, etc.). Usually, the powders of less than 1 um particle size are used for this purpose. Electroviscous-rheological suspensions also include activators adsorbed on the solid particles surface (glycerin, diethyleneglycol, amines, etc.) and stabilizers which are surfactants of ion and nonion types. Depending on the value of charge on the EEM friction parts lubricated with electroviscous-rheological suspension, its inter nal friction could increase up to an apparent solidification. The frictional joint structures based on this principle are used; to control loads in electric engines, to provide a fixed velocity of winding and unwinding threads, bands, cloth, etc. [8].

The capillary penetration of liquids into clearances in machine joints is one of urgent problems in assurance of articles tightness. The electret sealing of components could be a technologically simple approach of controlling the capillary leakage. Surface tension γ at the electrode-electrolyte boundary depends not only on the contacting media nature, but also on the properties of the dual electric layer as well. The equation of electric capillarity takes this regularity into account:

$$\gamma = \gamma_0 - 0.5C\varphi^2,$$

where, φ -electrode potential, γ_0-surface tension at $\varphi = 0$, C-capacity of the dual electric layer. The EEM surface charge density is to a large degree determining the value γ.

Crevice corrosion suppression with the help of engineering electret materials is based on the following concepts. The electrode potential (the differ-

ence the between galvanic electrode and electrolyte electric potentials) is a
basic characteristic of the dual electric layer at the electrode-electrolyte
interface. It determines the kinetics of electroviscous-chemical processes in a
clearance, where the electrode serves as a wall. Under the action of the
electret field the conducting electrons shift in the electrode, i.e. the electric
polarization of the electrode takes place (Fig. 5). This leads to variation in
the dual electric layer, which results in electroviscous-chemical polarization.
Since the clearance size in machine parts is small in comparison with the
contact surface microasperity height, the attenuation of the electret field in
the joint clearance is negligible. Thus, the polarization of the electrode in
the electret field could considerably change the electroviscous-chemical re-
actions in the clearance.

The effectiveness of EEM application as a means to inhibit the crevice
corrosion originates in the possibility of intensifying the adsorption of cor-
rosion inhibitors on the charged surface. By regulating the electret charge it
is possible to produce inhibitors concentration on the clearance-facing sur-
face sufficient for suppression of crevice corrosion.

The filtration systems efficiency has been improved by using EEM for
more than 30 years. The principle of a simplest filter operation is presented
schematically in Figure 6. A gas containing charged contaminant particles
is carried through the clearance between the electret and electrode. The
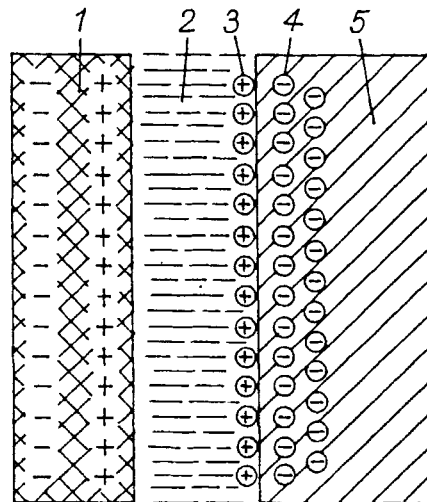
FIGURE 5   Scheme of electric polarization in the electret field. 1-electret; 2-electrolyte;
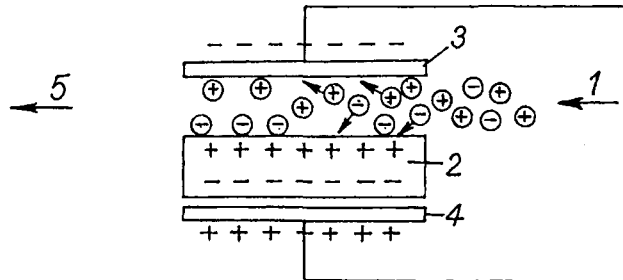3-particles of dual electric layer; 4-conductivity electrons, 5-electrode.

FIGURE 6 Diagram of electret filter operation. 1-contaminated gas flow; 2-electret; 3, 4-electrodes; 5-flow of purified gas.

latter is terminated in the second electrode located close to the oppositely charged electret surface [16]. The contaminant particles should precipitate, depending on their charge sign, either on the electret or electrode. Upon a certain volume of gas passes through the device, the electret element, as well as the electrode require cleaning to remove the deposited particles which screen the electret field.

To optimize operation of machines it is necessary to obtain the information on the processes of charge transfer, mass-and heat-exchange. A unique property of EEM is, that these materials can simultaneously fulfill the function of bearing and transferring mechanical loads, and the function of sensitive elements measuring these effects.

3. The Problems of EEM Development

EEM have been used in engineering for only about ten years. The principles of their development represent a new field in material science. The requirement of preserving the polarizing charge for the period during which the material meets the mechanical property criteria often comes into contradiction with the common requirements of composite materials. For example:

- special electric polarization methods in some cases negatively affect the dimensional precision of parts the structural integrity of material and its cost;
- introduction of electrically treated components into the binder could impair the composite production;
- the presence of electrical charge in structural materials often disturbs the interaction of machine parts and affects the serviceability of the neighboring joints and parts;

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