# CERTAIN LAWS OF CHARGE TRANSFER IN A FLUIDIZED BED OF A DISPERSED DIELECTRIC

V. A. Dovgyalo, S. F. Zhandarov,
and O. R. Yurkevich

An experimental study is made of charge transfer processes in a fluidized bed of a dispersed polymer. Features of the formation of the corona discharge are examined in relation to the parameters of the bed and the electric field. A steady-state hydrodynamic model is proposed for a fluidized bed of a unipolar dispersed dielectric. Calculations performed with the model agree satisfactorily with experimental results.

Many modern production processes involve the use of high-intensity physical phenomena — particularly strong electric fields. The interaction of electric fields with a strength up to $10^3$ kW/m and charges is the basis for electron-ion technology (electrostatic precipitation and electropainting, the production of composite materials, and the application of coatings composed of dispersed polymers). The realization of this interaction in the formation of prepregs of high-strength polymers is due to the mass transfer of a dielectric from a fluidized bed to the surface of the reinforcing filler in an electric field [1]. Two basic aspects of the interaction of the electric field and the charges of the particles of the dielectric should be noted: first of all, the field exerts a strong effect on the charged particles in the fluidized bed, leading directly to their mass transfer; secondly, the electric field can ionize dielectric particles in a fluidized bed. There have not been any studies of the physical laws underlying the interaction of an electric field and the charges of dielectric particles in fluidized beds which have explicitly taken into account the mechanical effects of the field and its ionizing ability. This subject has not been studied despite the fact that such interactions are the basis of many production processes and equipment designs [2, 3]. In the present article, we examine the results of an investigation of some of the laws governing charge transfer in a fluidized bed of dispersed thermoplastics. These materials are high resistivity dielectrics. The charge transfer processes were examined under the conditions of a unipolar corona discharge (CD).

In the course of the study, we determine the volt-ampere characteristic (VAC) of the discharge, i.e., the dependence of the current on the applied voltage. The literature [4] contains data on the VAC's of gas gaps of different geometries within a broad range of pressures. In contrast to pure gases, in fluidized beds of different materials the charge carriers are not only electrons and ions, but also the considerably heavier dispersed particles. Furthermore, these particles are characterized by a broad range of masses and dimensions, which has a significant effect on the VAC of the electrode gap. It should also be noted that the fluidization of dispersed charged dielectrics is characterized by certain purely hydrodynamic features which distinguish the process from the fluidization of neutral particles. Due to the existence of long-range repulsive forces between charged particles of the same type (under conditions of a unipolar CD), fluidization begins at a fluidizing-agent velocity which is lower than the usual velocity for fluidization (such as the value calculated by the method in [5]). These same forces are responsible for the absence of a clear upper boundary to the bed. The expansion of the bed is no longer characterized by height — a concept which has lost its physical significance in the given case — but by the characteristic scale $x_0$ of the change in the density of the bed. The initial height of the bed affects its density but does not affect $x_0$ (as will be shown below). As a result, in a fluidized bed of a charged dielectric there is always a region in which the concentration of particles is low. This region is usually the working region in most concrete applications of electron-ion technology and is the subject of investigation here.

TABLE 1. Certain Characteristics of the Polymers

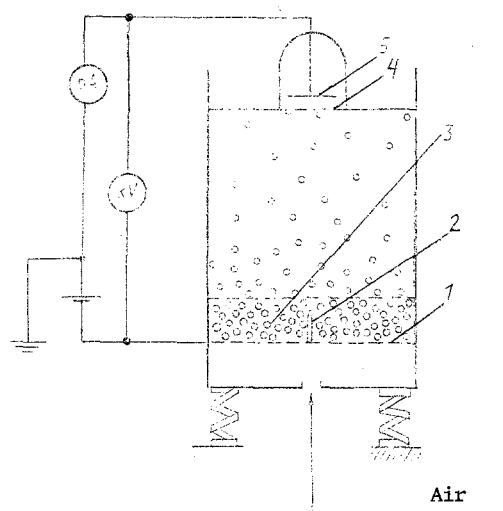| Polymer | Permittivity | Electrical resistivity, $\Omega \cdot m$ | Density, $10^3$ kg/m$^3$ |
|---------|--------------|------------------------------------------|--------------------------|
| Polyvinyl butyryl | 3,4 | $10^{12}$ | 1,1 |
| Polysulfone | 3,1 | $10^{13}$ | 1,2 |
| Foam plastic | 3,1 | $10^{14}$ | 1,4 |



Fig. 1. Sketch of experimental unit:
1) porous partition; 2) corona electrode; 3) fluidized bed; 4) grid; 5) collector.

Studies of the VAC were conducted on the unit sketched in Fig. 1. A fluidized bed of a dispersed polymer of a certain granulometric composition was created in the chamber of the vibro-vortical unit. The rate of flow of the fluidizing agent (air) during fluidization was $v = (1.4-4.0) \cdot 10^{-3}$ m$^3$/sec. Given that the cross-sectional area of the chamber $S = 4 \cdot 10^{-2}$ m$^2$, this flow rate corresponded to a working velocity of $(3.5-10) \cdot 10^{-2}$ m/sec. The velocity corresponding to the beginning of fluidization, calculated for the 315-400 μm fraction by the method in [5], was equal to $4 \cdot 10^{-2}$ m/sec. Vibration with maximum acceleration $b \geq g$ ensured efficient mixing of the particles in the horizontal plane. At lower values of b, the concentration of the bed became nonuniform across the chamber. This was particularly true in the absence of vibration. The frequency of the vibrations $f = 105$ Hz, close to the frequency of natural (resonance) vibrations of the unit, made it possible to attain the necessary accelerations. Further increases in b did not alter the electrical or hydrodynamic characteristics of the fluidized bed; acceleration b was set equal to 50 m/sec$^2$ in most of the experiments. Here, the amplitude of the vibrations was about $1.2 \cdot 10^{-4}$ m. The initial height of the bed changed within the range 15-35 mm. A voltage of up to 50 kV, monitored with an S-100 kilovoltmeter, was fed to the lower electrode. This was the electrode in contact with the fluidized bed. Part of the upper (deposition) electrode acted as charge collector. The current on this part of the electrode was recorded with a V7-30 electrometer. The collector was in the form of a disk whose dimensions were chosen so as to ensure adequate sentivity and exclude edge effects. The collector could be covered by a grid which detained particles of the powder. The mesh of the grid (0.8 mm) guaranteed not only that the grid would be completely opaque to the powder (even with the lowest intrinsic charge, due to static electricity, particles 50-100 μm in size were electrically deposited on the grid and returned to the bed after being discharged), but also that it would be sufficiently transparent to the ion current. The latter was measured by recording the VAC of the CD in pure air (without powder) and was 65%. The values of ion current given below were recalculated with allowance for this transparency.
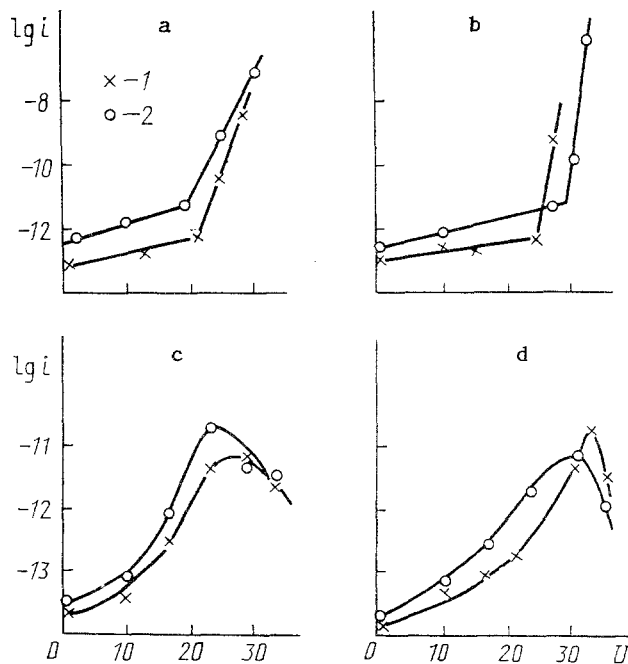
Fig. 2. Volt-ampere characteristics of fluidized
beds: a) polysulfone, d = 25 mm, $\ell$ = 60 mm; b)
polysulfone, d = 25 mm, $\ell$ = 110 mm; c) polyvinyl
butryl, d = 35 mm, $\ell$ = 60 mm; d) foam plastic, d =
35 mm, $\ell$ = 110 mm (1 — ion current; 2 — total cur-
rent). log i, A; U, kV.

We obtained the VAC's of fluidized beds of polysulfone (TU 605-211-939), polyvinyl
butyryl (STP 39-78), and foam plastic of grade Al (TU 605-1422-74) of different granulometric
compositions for different electrode gaps and bed heights. The choice of material was dic-
tated by the requirement that the uniformity of the fluidized bed be maximized. The part-
icles of all three of the chosen polymers were close to spherical and did not form agglo-
merates during fluidization in the experimental unit. Table 1 shows the electrical parameters
of the polymers we used and their density.

Figure 2 shows typical dependences of the total current in the system on voltage. The
total current in all of the regimes was 20-40% of the current recorded by the collector with-
out the grid. The point of inflection on the curve corresponds to the appearance of the CD.

The results of our measurements show that changing the electrode gap $\ell$ does not change
the form of the VAC and has a significant effect only on the voltage at which the CD appears:
with an increase in $\ell$, inducing the discharge requires an increase in the potential difference
between the electrodes. The dependence of the discharge current on the applied voltage is
nearly the same for all three materials used in the experiment. This can be attributed to
the similar permittivities and densities of polysulfone, polyvinyl butryl, and the foam
plastic. As a result, fluidized beds of these materials (in which the degree of dispersion
of the particles is the same) have comparable electrical and hydrodynamic parameters. At
the same time, the initial height of the bed d has a strong influence on the characteristics
of the CD. By increasing d, it is even possible to completely suppress the corona discharge
(Fig. 2, c and d).

The VAC's that were obtained show that the presence of a CD significantly changes the
relative contributions of different mechanisms to the charging of particles of the dispersed
material. Whereas static electricity is most important [6] in the absence of a corona, when
it is present the main method of charging becomes the deposition of ions on the surface of
the particles. Although the contribution of the laternative mechanism (static electricity)
does not decrease in the absolute sense, it can be ignored compared to ion deposition. The
appearance of the CD is accompanied by a sharp increase both in the total current of ions and
in their difference — the current of particles. In the absence of the CD, the particle cur-
rent is considerably less at the same given potential. This is evidence that the ions of the
CD make the main contribution to the charging of the powder particles. An increase in par-

TABLE 2. Parameters of the VAC of Fluidized Beds of Poly-
sulfone of Different Disperse Compositions ($\ell$ = 60 mm, d =
25 mm)

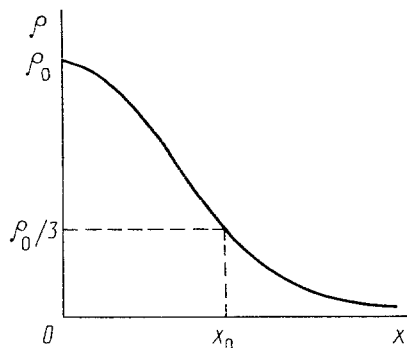| Particle diameter, mm | Breakdown voltage, kV | Corona discharge current, A |
|---|---|---|
| 0,050—0,100 | 29 | $4,2 \cdot 10^{-9}$ |
| 0,315—0,400 | 31 | $3,7 \cdot 10^{-12}$ |



Fig. 3. Theoretical dependence of the
density of the fluidized bed on its
height.

ticle concentration in the electrode gap (such as would occur with an increase in the ini-
tial height of the bed d) is accompanied by a decrease in both the ion current (some of the
ions are deposited on particles) and in the total current of the gas discharge. The latter
reduction is connected with a decrease in the average mobility of the charge carriers.

The experiments established that the VAC of the fluidized bed is significantly influ-
enced by the dispersity of the material. A change in particle diameter from 60 to 315 μm
(i.e. by a factor of 5-6) leads to a drop in the CD current by about three orders of magnitude
(Table 2). The change in the breakdown voltage here is negligible, which is difficult to ex-
plain just on the basis of electrostatics. In fact, if it is assumed that the strength of the
electric field at the surface of the particles is the same for particles of different sizes
(and is close to the breakdown strength — which is characteristic of a corona discharge),
then the specific charge of particle $q/m \sim \sigma a^2/a^3 \sim a^{-1}$. The acceleration with which a part-
icle is removed from the fluidized bed is proportional to the specific charge: $w = F/m \sim Eq/m$ .
Thus, $w \sim a^{-1}$, which with a change in a by a factor of 5-6 should lead to a change in current
only by the same factor. Attributing the relation i(a) to a change in the permittivity of
the fluidized bed is also unsatisfactory. First of all, the permittivities of the dispersed
materials we tested were no greater than four, and none of the changes we made in the fluid-
ized bed (in its density, the dispersity of the particles, the rate of mixing) changed the
value of $\varepsilon$ of the bed by a factor of more than four. Secondly, the change in $\varepsilon$ affects not
so much the CD current as the breakdown voltage. Thus, when analyzing the dependence of the
VAC on dispersity, allowance should also be made for the hydrodynamic factor — specifically,
for the change in the concentration of the disperse phase with height. This change is deter-
mined on the one hand by the granulometric composition of the particles and, on the other
hand, by their charged state (which leads to mutual repulsion). The concentration of charged
particles near the deposition electrode determines the flow of these particles to the col-
lector, i.e., the recorded current.

Both factors are accounted for by the steady-state hydrodynamic model of a charged
fluidized bed. A particle of radius a and charge q in a fluidized bed at the height x in a
cylindrical channel is acted upon by three forces: gravity m$\bar{g}$; the Stokes forces from the
direction of the fluidizing gas $6\pi\eta a\bar{u}(x)$; the electrostatic force $E q$. The magnitude of $\bar{E}$
depends on the potential difference applied to the electrodes, charge density over the volume
of the fluidized bed, and the geometry of the system. For simplicity, we will henceforth
examine a system of flat electrodes of large area. We further assume that the dimensions of
all of the particles are the same and are equal to a; the charges of all of the particles
are also the same and equal to q. The last assumption means in particular that the contribu-
tion of static electricity to the charging of the particles — where charges of both signs

appear — is negligibly small; the particles may be charged either by means of a corona discharge or by some other external unipolar ionizer (such as an electron beam or ion beam). As will become evident from the subsequent analysis, the model also satisfactorily describes the behavior of a fluidized bed of a polydisperse dielectric. Here, the charge density is determined by the concentration of the smallest fraction.

Thus, the strength of the electric field in the system in question is equal to

$$E = \frac{U}{l} + \frac{1}{2\varepsilon_0\varepsilon}\left(\int\limits_0^x \rho\,(h)\,dh - \int\limits_x^{+\infty} \rho\,(h)\,dh\right).$$

In the equilibrium state, the sum of all three forces acting on the particle is equal to zero:

$$m\mathbf{g} + \mathbf{E}q + 6\pi\eta a\mathbf{u}\,(x) = 0,$$

or in a projection on the vertical axis

$$mg - \frac{U}{l}q - \frac{q}{2\varepsilon_0\varepsilon}\left(\int\limits_0^x \rho\,(h)\,dh - \int\limits_x^{+\infty} \rho\,(h)\,dh\right) = 6\pi\eta a u\,(x). \tag{1}$$

The density of the fluidized bed should be quite low in this case:

$$\varkappa \equiv \frac{4\pi a^3 \rho}{3q} \lesssim \frac{1}{2}. \tag{2}$$

Otherwise, a quasisolid phase will appear near the bottom of the chamber. The level of mechanical interaction between particles will be high in this phase, so that the Stokes formula will not be applicable. If we make condition (2) stronger and take χ << 1, then the fluidizing gas can be assumed to be incompressible and we can write the continuity equation as the volume conservation law for it:

$$u\,(x)\,S_{\text{por}}\,(x) = v = \text{const.} \tag{3}$$

Since $S_{\text{por}}\,dx + dV_{\text{free}}$, $Sdx = dV$, then

$$dV_{\text{free}} = dV - dV_{\text{part}} = Sdx - \frac{4\pi a^3 \rho\,(x)}{3q}\,Sdx = S\left(1 - \frac{4\pi a^3 \rho\,(x)}{3q}\right)dx.$$

With allowance for this, we find from (3) that

$$u\,(x) = \frac{3qv}{S\,(3q - 4\pi a^3\rho)}\,.$$

Having inserted this expression into (1), we obtain an equation relative to ρ:

$$mg - \frac{U}{l}q - \frac{q}{2\varepsilon_0\varepsilon}\left(\int\limits_0^x \rho\,(h)\,dh - \int\limits_x^{+\infty} \rho\,(h)\,dh\right) = \frac{18\pi\eta a q v}{S\,(3q - 4\pi a^3\rho)}\,. \tag{4}$$

Differentiating (4) with respect to x, we arrive at the ordinary differential equation

$$-\frac{\rho(x)}{\varepsilon_0\varepsilon} = \frac{72\,\pi^2 a^4 \eta v}{S\,(3q - 4\pi a^3 \rho(x))^2}\,\rho'(x).$$

Its solution with the condition $\rho|_{x=0} = \rho_0$ is

$$x = A\left(\frac{1}{3q}\ln\frac{\rho_0(3q - 4\pi a^3\rho)}{\rho(3q - 4\pi a^3\rho_0)} + \frac{1}{3q - 4\pi a^3\rho} - \frac{1}{3q - 4\pi a^3\rho_0}\right), \qquad (5)$$

where

$$A = \frac{24\pi^2 a^4 \eta v \varepsilon_0\varepsilon}{qS}.$$

Having solved (5) for $\rho$, we obtain the relation $\rho(x)$ shown in Fig. 3. At $\kappa \ll 1$, i.e., at low particle concentrations, $\rho \sim \exp(-x/x_0)$, where the parameter $x_0 = 8\pi^2\eta a^4\varepsilon_0\varepsilon/(q^2 S)$ corresponds to the characteristic distance at which the particle concentration in the fluidized bed decreases by the factor e.

The dependence of charge density on height is of an exponential character. Since $x_0 \sim a^4$, $\rho \sim \exp(-V^* x/a^4)$, where $V^*$ is a constant. With a doubling of a, $\ln\rho$ at a fixed height decreases by a factor of 16. This is accompanied by a corresponding reduction in $\rho$.

Thus, although the specific surface of the particles near the bottom of the chamber is proportional to a (with satisfaction of the conditions $\rho_0 = \text{const}$, $v = \text{const}$), at the height $x \neq 0$ it is proportional to $a\exp(-V^* x/a^4)$. This in the final analysis leads to a sharp decrease in particle current with an increase in particle size. The same outcome is seen for the ion currents in the experiment. This fact and the constancy of the ratio $i_i/i$ within a broad range of densities are evidence of the existence of dynamic equilibrium during particle charging-discharging and are indirect proof that the particles are charged mainly as a result of the deposition of ions — since the competing mechanism of static charging is a nonequilibrium process.

Numerical calculations performed for $a_1 = 25$ μm and $a_2 = 150$ μm give the following (with the test conditions $\eta = 1.8\cdot10^{-5}$ kg(m.sec), $v = 2\cdot10^{-3}$ m³/sec, $S = 4\cdot10^{-2}$ m²)

$$\frac{x_{02}}{x_{01}} \sim 7\cdot10^{-4},$$

which corresponds to the experimental current ratio.

Thus, charge transfer through a fluidized bed of a dispersed dielectric material depends mainly on the hydrodynamic properties of the bed. By regulating the density of the bed and thus the current on the deposition electrode, it is possible to control the regimes by which a disperse binder is deposited on a filler in the production of prepregs for composite materials.

### NOTATION

$\ell$, distance between electrodes; d, initial height of the fluidized bed; q, m, a, charge, mass, and radius of a particle; $\tau$, surface charge density on the particle; E, strength of the electric field; i, $i_i$, total current in the system and its ionic component; $\varepsilon$, permittivity; g, acceleration due to gravity; $\eta$, absolute viscosity of the gas; u, velocity of the gas relative to the particle in a given section; U, interelectrode potential difference; $\varepsilon_0$, permittivity of vacuum; S, area of cross section of bed; $\rho(x)$, electric charge density in the bed at the height x; h, running coordinate; $\kappa$, dimensionless density of the fluidized bed; v, rate of flow of the fluidizing gas; $S_{por}(x)$, area of pores in a given section ; dV, $dV_{free}$, volume element and the part of the volume element which is free of particles.

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# NUMERICAL MODELING OF HEAT AND MASS TRANSFER DURING THE DRYING

# OF GRANULATED POLYMERS IN A PACKED BED

N. A. Prudnikov, M. A. Brich,                                          UDC 66.047
and Ya. S. Raptunovich

A model is proposed for calculating heat and mass transfer in a packed bed exposed to a drying agent. Results are presented from a numerical realization of the model for the drying of granulated polyamide of type PA-6.

In connection with the continual and substantial increase in the volume of plastics that is processed in industry, the drying of these materials has become an important issue. Processing plants currently use several different drying methods — vacuum drying, drying in fluidized beds, and convective drying. Meanwhile, there are no scientifically substantiated recommendations on the most expedient drying methods for different types of materials. The goal of the present investigation is to numerically model the high dessication of a dispersed polymer in a packed bed injected with dried air.

We know of several studies which have examined similar problems [1-4]. However, either the methods used in these studies are too laborious or the formulations involve limitations that make it difficult to obtain detailed results.

For example, the authors of [1-3] examined internal mass transfer on the basis of the equations of A. V. Lykov. Such an approach complicates the problem excessively for materials such as polymides, polycarbonates, and ABS-plastics. First of all, considering the relatively small dimensions of the grains, the temperature gradients which develop inside them during normal heating regimes should not be very large. Thus, it is possible to exclude the heat-conduction equation for the grains and to ignore thermodiffusional transport of mositure. Secondly, the evaporation of moisture in such materials occurs only on the surface of the grains, since there is almost no capillary-pore structure inside them. Thus, it also makes no sense to employ a phase transformation criterion. The main advantage of the model used in [4] is the use of enthalpy instead of temperature to describe the energy state of the medium. Such an approach permits a thermodynamically more rigorous accounting of processes involving the transport of moisture between the air and the material. At the same time, this model does not contain a diffusion equation and thus may yield sizable errors for materials with a large diffusional component. It also fails to account for certain other physical factors, such as changes in injection rate in relation to an increase or decrease in the quantity of water vapor in the gas-air flow.

The model of the process which we propose here provides a better foundation for allowance for all of the main factors in the process while not being excessively difficult in a methodological sense. The following physical limitations are used in the model: the material is