7. K. V. Krishna Rao, S. V. Nagender Neifu, and P. L. N. Setty, Acta Crystallogr., 15, 528 (1962).
8. K. Kogama, J. Amer. Ceram. Soc., 52, 222 (1969).
9. V. V. Gorlach and V. M. Lishuin, Fiz. Tverd. Tela, 16, 1988 (1974).
10. G. Leibfried and E. Schlemann, Nachrichten der Akad. der Wissen. in Göttingen, 11a, 4 (1954).
11. M. N. Ecombe and A. W. Prior, J. Phys. C. Solid State Phys., 3, 492 (1970).
12. F. K. Volynets and G. N. Dronova, Fiz. Tverd. Tela, 11, 1867 (1962).
13. C. L. Julian, Phys. Rev., 137, A 128 (1965).
14. M. Roufosse and R. G. Klemens, Phys. Rev., B, 7, 5379 (1973).
15. L. Croatto, Gazz. Chim. Ital., 74, 20 (1944).
16. B. M. Mogilevskii, V. F. Tumpureva, and A. F. Chudnovskii, Inzh.-Fiz. Zh., 27, 287 (1974).
17. B. F. Ormont, Structures of Inorganic Substances [in Russian], Gostekhizdat, Moscow–Leningrad (1950).

ELECTRIFICATION OF A PNEUMATIC TRANSPORT FLOW AND A DIELECTRIC PIPE WITH HOMOGENEOUS SURFACE PROPERTIES

V. N. Verevkin, R. A. Yailiyan, and B. G. Popov

UDC 621.867.8

The basic parameters of contact electrification are established for the interaction of a dispersed flow with the lateral surface of a pipeline; methods of determining the parameters experimentally are indicated, together with their practical application.

The formation and separation of contacts between systems of dispersed particles and the surfaces of industrial apparatuses, machine parts, transporting equipment (conveyers), bunkers, and silos take place in the course of many widely employed processes and commercial operations. After each contact a charge density σ_0 is created on the area of contact between the dispersed particle and the wall (solid surface); its value depends on the physicochemical properties of the surfaces in contact [1-3]. In systems in which the linear dimensions of the spot are 0.05 mm or under [4], no gas discharge occurs in the space between the separating surfaces. Electric exchange between the particle and the wall remains basically governed by the invariance of the parameters of the electric double layer: its thickness, the difference in work function corresponding to the transfer of ions or electrons from one phase to the other, and the electric induction vector. The particles in the flow touch the dielectric wall, which already bears a charge density σ (Fig. 1). Under the influence of the external field E due to the exchange charge density of the flow and as a result of the polarization of the particle, the contact area develops the following charge density [5]:

$$\sigma_1 = \alpha E. \tag{1}$$

The polarization coefficient α depends on the material, shape, and position of the particle at the moment of contact with the wall. The total induction vector in the electric double layer is governed by σ, σ_1, and the charge density σ_r associated with the formation of the electric double layer:

$$\sigma_0 = \sigma_r + \alpha E + \sigma. \tag{2}$$

If electric exchange between the system of dispersed particles and the surface occurs as a result of contact between particles obeying Eq. (2), the following electrification current density will flow in each section of the surface:

$$j = \beta\sigma_r = \beta(\sigma_0 - \alpha E - \sigma). \tag{3}$$

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 30, No. 2, pp. 328-333, February, 1976. Original article submitted January 2, 1975.

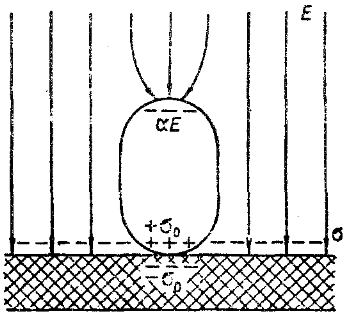

Fig. 1

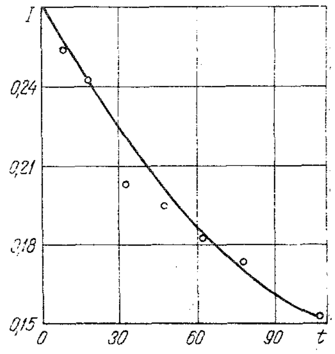

Fig. 2

Fig. 1. Principle of electrification after the collision of a particle with a charged dielectric surface in the presence of an electric field E.

Fig. 2. Time dependence of the electrification current of a 13v glass tube 330 mm long and 38 mm in diameter during the pneumatic transport of wheat flour having a particle size of 120 μ and a 12% moisture content at a rate of 11 m/sec and a concentration of 1.7 kg/kg.

The parameter β characterizes the local density of the contacts between the system of dispersed particles and the wall. This is numerically equal to the total area of the contacts between the dispersed system and unit wall surface renewed in unit time.

Information as to the values of σ_0 and α, and also as to the equilibrium electric field at which the mutually opposed processes of contact electrification and the polarization of the particles in the electric field of the charges of the dispersed system are in balance, is extremely useful when studying (or executing an engineering analysis of) the electrical phenomena arising from contact between the particles and the walls.

Earlier it was shown [6] that E_p could be determined by measuring the electrification current of a long pneumatic-transport pipeline.

The value of σ_0 and β may be determined in a laboratory pneumatic-transport apparatus [7] from the diagram representing current changes in the grounding circuit of the outer conducting coat of a short dielectric tube (Fig. 2). No rapid changes should take place in the physicochemical properties of the dielectric surface under these conditions. Adhesion, the formation of coatings of the transported material on the wall, and the development of electric discharges should be eliminated.

The fundamental possibility of calculating σ_0 and β from the current diagram follows from Eq. (3). If the flow in the inlet section is uncharged, the tube is "short," and the current in the grounding circuit of the outer conducting coat is measured under conditions in which $\sigma = 0$, we have

$$j_0 = \beta\sigma_0. \tag{4}$$

After a time $t \ll \tau$ the following charge density is created on the dielectric surface:

$$\sigma_t = 0.5\,(j_0 + j_t)\,t \tag{5}$$

and the electrification current density becomes

$$j_t = \beta[\sigma_0 - 0.5\,(j_0 + j_t)t]. \tag{6}$$

It follows from (4) and (6) that

$$\sigma_0 = \frac{(j_0 + j_t)\,t}{2\left(1 - \frac{j_t}{j_0}\right)}, \tag{7}$$

$$\beta = \frac{2}{t} \cdot \frac{j_0 - j_t}{j_0 + j_t}. \tag{8}$$

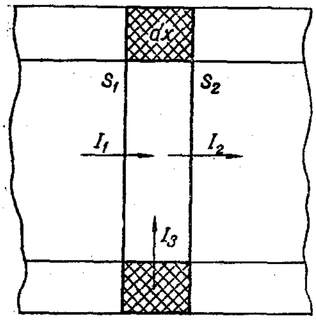

Fig. 3. Basic scheme of electric exchange between the flow and a section of tube wall.

The volumetric charge density has no effect on the calculation of β but influences the accuracy of the determination of σ_0. Thus, if the volumetric charge densities at the inlet and outlet cross sections, respectively, equal ρ_0 and ρ_L, we must add the following to the right-hand side of Eq. (7):

$$\frac{(\rho_0+\rho_L)\,\alpha D}{8\varepsilon\varepsilon_0}.$$

In order to calculate the charge density on the surface of the dielectric tube and in the flow at any arbitrary instant of time and at any arbitrary point, let us analyze the electric exchange of the flow with an annular section of wall (Fig. 3).

If we successively apply the law of charge conservation to unit volume in the interior of the ring and to the lateral surface, we have

$$\frac{\partial\rho}{\partial x}=\frac{4\beta}{Dv}(\sigma_0-\sigma-\alpha_1\rho),$$
$$\frac{\partial\sigma}{\partial\Theta}=\frac{D}{4}\frac{\partial\rho}{\partial x}-\frac{\sigma}{v\tau} \qquad (9)$$

with the following initial and boundary conditions:

$$\rho(0,\,\Theta)=f_1(\Theta),\quad \sigma(x,\,0)=f_2(x). \qquad (10)$$

Here we have assumed that the surface conduction current is negligibly small.

After introducing the notation

$$U=\frac{\alpha_1\rho}{\sigma_0};\quad V=\frac{\sigma}{\sigma_0};\quad x_1=\frac{4\beta\alpha_1}{Dv}x;\quad x_2=\frac{\beta}{v}\Theta;\quad a=\frac{1}{\beta\tau}$$

we obtain

$$\frac{\partial U}{\partial x_1}+U+V=1;\quad U(0,\,x_2)=F_1(x_2);$$
$$\frac{\partial V}{\partial x_2}+aV=\frac{\partial U}{\partial x_1};\quad V(x_1,\,0)=F_2(x_1). \qquad (11)$$

Let us apply a Laplace transformation in x_1 to the system (11):

$$sU-F_1(x_2)+\bar U+\bar V=\frac{1}{s}, \qquad (12)$$

$$\frac{\partial V}{\partial x_2}+aV=s\bar U-F_1(x_2),$$
$$\bar V(s,\,0)=\bar F_2(s). \qquad (13)$$

The solution of (12) subject to the condition (13) is

$$\bar V=\int_0^{x_2}\frac{1-F_1(x_2-z)}{s+1}\exp\left[\frac{z}{s+1}-(a+1)z\right]dz+\bar F_2(s)\exp\left[\frac{x^2}{s+1}-(a+1)x_2\right]; \qquad (14)$$

$$\bar U=\frac{1}{s}-\frac{1}{s+1}+\frac{F_1(x_2)}{s+1}-\int_0^{x_2}\frac{1-F_1(x_2-z)}{(s+1)^2}\exp\left[\frac{z}{s+1}-(a+1)z\right]dz-\frac{F_2(s)}{s+1}\exp\left[\frac{x_2}{s+1}+(a+1)x_2\right]. \qquad (15)$$

The originals corresponding to (14) and (15) take the form

TABLE 1. Values of β Characteristic of the Pneumatic-Transport Flow of Wheat Flour in Dielectric Tubes

Tube material	v, m/sec	μ, kg/kg	β, m²/m²·sec
Molybdenum glass	14 17,7	2,5 1,74	0,0058 0,0049
13v glass	10,7	1,74	0,0038
Vinyl sheet	17,2	3,54	0,0051
Polyethylene MRT-6-05-1169	10,8	3,54	0,0066

$$U = 1 - \exp(-x_2)[1 - F_1(x_2)[-\exp(-x_1)\int_0^{x_2}[1 - F_1(x_2 - z)]\, I_1(2\sqrt{x_1 z})\sqrt{\frac{x_1}{z}}\exp[-(a+1)z]\,dz - \exp[-(a+1)x_2]\int_0^{x_1} I_0(2\sqrt{x_2 w})\, F_2(x_1 - w)\exp(-w)\,dw; \quad (16)$$

$$V = F_2(x_1)\exp[-(a+1)x_2] + \exp[-(a+1)x_2\int_0^{x_1} F_2(x_1 - w)\exp(-w)\, I_1(2\sqrt{x_2 w})\sqrt{\frac{x_2}{w}}\,dw + \exp(-x_1)\int_0^{x_2}[1 - F_1(x_2 - z)]\, I_0(2\sqrt{x_1 z})\exp[-(a+1)z]\,dz. \quad (17)$$

When studying σ_0, α, and β in laboratory installations it is simplest to realize conditions in which at the initial instant of time the tube wall is unchanged, while the charge density of the flow in the inlet section is constant, i.e.,

$$\sigma(x,\ 0) = 0 \ \text{ and } \ \rho(T) = \rho_0.$$

The solutions of (16) and (17) for the volumetric and surface charge densities in the flow and on the wall, respectively, may then be written

$$\rho(x,\ T) = \frac{4\varepsilon\varepsilon_0\sigma_0}{\alpha D}\left\{1 - \exp\left(-\frac{\alpha\beta x}{\varepsilon\varepsilon_0 v}\right)\left(1 - \frac{\alpha D}{4\varepsilon\varepsilon_0}\frac{\rho_0}{\sigma_0}\right)\left[1 + \int_0^{\beta\left(T - \frac{x}{v}\right)} I_1\left(2\sqrt{\frac{\alpha\beta}{\varepsilon\varepsilon_0 v}xz}\right)\sqrt{\frac{\alpha\beta}{\varepsilon\varepsilon_0 v}\frac{x}{z}}\exp\left[-\left(\frac{1}{\beta\tau}+1\right)z\right]dz\right]\right\}; \quad (18)$$

$$\sigma(x,\ T) = \sigma_0\exp\left(-\frac{\alpha\beta x}{\varepsilon\varepsilon_0 v}\right)\left[1 - \frac{\alpha D}{4\varepsilon\varepsilon_0}\frac{\rho_0}{\sigma_0}\right]\int^{\beta\left(T - \frac{x}{v}\right)} I_0\left(2\sqrt{\frac{\alpha\beta}{\varepsilon\varepsilon_0 v}xz}\right)\exp\left[-\left(\frac{1}{\beta\tau}+1\right)z\right]dz. \quad (19)$$

Analysis of (18) and (19) with due allowance for the Weber integrals leads to the conclusion that in the case of prolonged transportation

$$\rho(x) = \frac{4\varepsilon\varepsilon_0\sigma_0}{\alpha D}\left\{1 - \left(1 - \frac{\alpha D}{4\varepsilon\varepsilon_0}\frac{\rho_0}{\sigma_0}\right)\exp\left[-\frac{\alpha\beta x}{\varepsilon\varepsilon_0 v(1+\beta\tau)}\right]\right\}, \quad (20)$$

$$\sigma(x) = \sigma_0\left(1 - \frac{\alpha D}{4\varepsilon\varepsilon_0}\frac{\rho_0}{\sigma_0}\right)\exp\left[-\frac{\alpha\beta x}{\varepsilon\varepsilon_0 v(1+\beta\tau)}\right]. \quad (21)$$

If the transportation time is short,

$$\rho(x,\ T) = \frac{4\varepsilon\varepsilon_0\sigma_0}{\alpha D}\left\{1 - \left(1 - \frac{\alpha D}{4\varepsilon\varepsilon_0}\frac{\rho_0}{\sigma_0}\right)\exp\left(-\frac{\alpha\beta x}{\varepsilon\varepsilon_0 v}\right)\left[1 + \frac{\alpha\beta x}{\varepsilon\varepsilon_0 v}(\beta T - 1)\right]\right\}; \quad (22)$$

$$\sigma(x,\ T)=\sigma_0\beta T\left(1-\frac{\alpha D}{4\varepsilon\varepsilon_0}\frac{\rho_0}{\sigma_0}\right)\exp\left[-\frac{\alpha\beta x}{\varepsilon\varepsilon_0 v(1+\beta\tau)}\right]. \qquad (23)$$

The foregoing considerations were of fundamental importance when analyzing the permissibility of using dielectric pipes in pneumatic-transport lines. The use of dielectric materials is permissible if the charge density arising on the walls is no greater than 0.4 σ_{lim}.

Investigations showed, for example, that for wheat flour with a 120-μ grain and a moisture content of 12-13%, $\alpha \approx 6 \cdot 10^{-9}$, while the values of σ_0 for pneumatic-transport pipes made of molybdenum glass, 13v glass, vinyl sheet, polyethylene (MRT-6-05-1169), duralumin, and steel, respectively, equal −2400; −2000; −1600; − 580; andfrom −600 to −1000 μc/m^2. The observed values of β are presented in Table 1.

NOTATION

D, diameter of pipe; E, electric field; $I_{1,2,3}$, currents through inlet and outlet cross sections and the lateral surface of a pipe section; j, current density; $j_{v,s}$, current densities through volume and surface resistances; v, mean air speed; t, local time; T, time from the initial instant of the transport process; x, stationary coordinate axis with origin in the inlet section; α, particle polarization coefficient; β, density of the contacts between the surface of the pipe and the solid phase renewed in 1 sec; ε and ε_0, relative and absolute dielectric constants; Θ, movable coordinate axis, its origin coinciding with the front of the flow; ρ, volumetric charge density; σ, σ_0, surface charge density and charge density characterizing the contact pair; $\tau_{1,s}$, characteristic charge leakage time through the volumetric and surface resistances of the pipeline.

LITERATURE CITED

1. B. V. Deryagin and N. A. Krotova, Adhesion [in Russian], Izd. Akad. Nauk SSSR (1949).
2. B. V. Deryagin and I. N. Aleinikova, in: Surface Force Studies [in Russian], Izd. Akad. Nauk SSSR (1961), p. 72.
3. I. N. Aleinikova, B. V. Deryagin, and Yu. P. Toropov, Kolloidn. Zh., 30, 177 (1968).
4. V. I. Gorshkov, B. G. Popov, and V. N. Verevkin, Teor. Osnovy Khim. Tekhnol., No. 2, 905 (1968).
5. L. D. Landau and E. M. Lifshits, Electrodynamics of Continuous Media, Addison-Wesley (1960).
6. V. N. Verevkin and V. I. Gorshkov, Izv. Vyssh. Uchebn. Zaved., Pishch. Tekh., No. 1, 134 (1970).
7. B. G. Popov, V. N. Verevkin, V. A. Bondar', and V. I. Gorshkov, Static Electricity in the Chemical Industry [in Russian], Khimiya, Leningrad (1971).
8. A. Angot, Mathematics for Electrical and Radio Engineers [Russian translation], Nauka, Moscow (1967), pp. 536, 396.
9. A. Gray, G. B. Mathews, and T. M. MacRobert, Treatise on Bessel Functions and Their Application to Physics (2nd ed.), Macmillan, New York (1922).