CHARGE TRANSFER IN TWO-PHASE (GAS – SOLID-PARTICLE) FLOWS

B. G. Popov

UDC 621.547:537.24

The contact charging of a single solid particle in contact with a plane wall and of a particle flux bounded by a cylindrical wall is considered.

In technological processes accompanied by disruption (separation) of surfaces, the formation and accumulational of electrical charges is observed. This effect, which becomes more significant as technological processes intensify, has many undesirable consequences. Electrical charges forming on solid surfaces result in increased adhesion, electrical breakdown, and mechanical failure of components. The resulting continuous spark discharges in the apparatus increase the risk of ignition and explosion of the hot medium [1, 2].

In any closed technological process (pneumotransport of free-flowing material, treatment in fluidized-bed equipment, etc.) three regions may be distinguished: separation of the electric charges, transfer of electric charges, and discharge (recombination) of the charges.

In the separation region solid particles acquire an electrical charge, and are then transferred to the discharge region, where the charge is discharged to the wall (is recombined). The electric circuit is closed by the wall of the apparatus or by the earth.

The investiation begins with a consideration of the electrical processes accompanying the disruption of the contact surfaces between a single particle and a plane wall.

Subsequently, attention turns to electrical processes accompanying the motion of a particle flux bounded by a cylindrical conducting wall.

It is postulated that at the contact between the particle and the wall a double electrical layer of charge density σ_{DL} is formed.

The charge acquired by a single particle on contact with the wall is determined on the following assumptions: That the particle is electrically neutral prior to contact with the wall; that there is no electric field external to the particle; that contact occurs in the elastic-strain region.

At contact, the particle acquires a charge

$$Q_p = \sigma_{DL} S_C \tag{1}$$

In the separation (disruption) of the surfaces (separation of the particle from the wall) the electrical charge is discharged through the ohmic resistance of the contact surfaces (Q_{ohm}) and is neutralized as a result of ionic processes occurring in the gap between the two surfaces after separation (Q_I) Fig. 1).

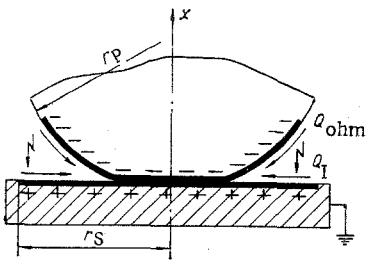

Fig. 1. Contact of spherical particle with plane wall.

Moscow Institute of Chemical Engineering. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 34, No. 1, pp. 50-57, January, 1978. Original article submitted October 1, 1976.

0022-0841/78/3401-0031 $07.50

Taking these processes into account, the electric charge of the particle after separation from the wall will be

$$Q_P = \sigma_{DL} S_C - Q_{ohm} - Q_I . \tag{2}$$

The charge density on the two surfaces depends slightly on the electrical resistance for constant surfaces with electrical resistance of 10^8 Ω or more [2]. In this case the charging is self-regulating as a result of ionic processes occurring in the gas discharge between the two surfaces after separation. The charge dissipation in this case is

$$Q_I = ez \int_V n(V)\, dV. \tag{3}$$

The charge on the particle after contact is broken will be

$$Q_P = \sigma_{DL} S_C - ez \int_V n(V)\, dV. \tag{4}$$

In the case of contact surfaces of resistance less than 10^8 Ω, charge dissipation occurs through the ohmic resistance of the surfaces and no ionic processes are seen in the gap [2].

In this case, Eq. (2) takes the form

$$Q_P = \sigma_{DL} S_C - Q_{ohm} \tag{5}$$

The charge on the contact surfaces after separation is not retained if $\sigma_{DL} S_C = Q_{ohm}$.

In this case the equation describing the discharge of the electric charge through the ohmic resistance of the contact surfaces is

$$\gamma E_G = \frac{d\sigma}{dr_S} v_0. \tag{6}$$

For the boundary condition $\sigma = \sigma_{DL}$ as $r_S \to 0$, the solution of Eq. (6) is

$$\sigma = \sigma_{DL} \exp\left(-\frac{\gamma r_S}{\varepsilon\varepsilon_0 v_0}\right). \tag{7}$$

The total electric charge acquired by the particle at the wall is

$$Q_P = \int_S \sigma(s)\, ds. \tag{8}$$

For a spherical particle, the solution of Eq. (8) takes the form

$$Q_P = 2\pi\sigma_{DL}\left[\frac{r_S \varepsilon\varepsilon_0 v_0}{\gamma} \exp\left(-\frac{\gamma r_S}{\varepsilon\varepsilon_0 v_0}\right) + \left(\frac{\varepsilon\varepsilon_0 v_0}{\gamma}\right)^2 \exp\left(-\frac{\gamma r_S}{\varepsilon\varepsilon_0 v_0}\right) - \left(\frac{\varepsilon\varepsilon_0 v_0}{\gamma}\right)^2\right]. \tag{9}$$

It is evident from Eq. (9) that the charge at the contact surfaces after separation is a maximum when $\gamma r_S \to 0$, i.e., $r_S \to 0$ or $\gamma \to 0$, and is a minimum when $\varepsilon\varepsilon_0 v_0 \to 0$ or $\gamma r_S \to \infty$. The intensity of charging may be estimated from the value of the dimensionless number

$$K_c = \frac{\varepsilon\varepsilon_0 v_0}{\gamma r_S}. \tag{10}$$

The dimensionless number in Eq. (10) characterizes the ratio of the convective charge-transfer component to the charge relaxation as a result of the conduction of the contact surfaces. The charging intensity increases with rise in K_c.

The results obtained are confirmed by the practical recommendations intended to decrease charging charging decreases with decrease in the velocity of moving dielectric materials, according to technological reports.

As charge dissipation in the gap as a result of ionic processes has not been adequately studied, the problem cannot be solved analytically and quantitative results may only be obtained experimentally. An experimental investigation was carried out to provide qualitative verification of the hypothesis that the dissipation of electrical charges at separating dielectric surfaces occurs as a result of ionic processes occurring in the gap.

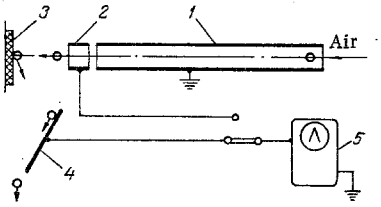

Fig. 2

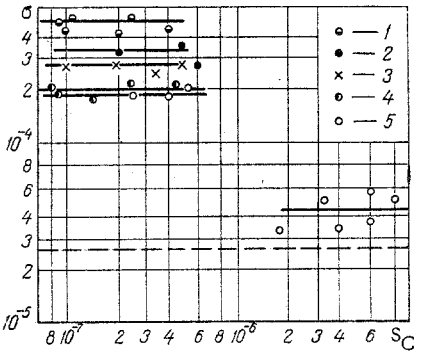

Fig. 3

Fig. 2. Experimental apparatus to investigate the charging of conducting particles on collision with a dielectric surface: 1) pneumatic tube; 2) measuring section of tube; 3) dielectric target; 4) electrode for collection of particle charge; 5) oscillograph.

Fig. 3. Charge density as a function of the contact area between the steel ball and the dielectric surface: 1) polyethylene terphthalate (film) target, ball diameter 1.5 mm; 2) ball diameter 3.7 mm; 3) polystyrene (film) target, ball diameter 1.5 mm; 4) ball diameter 3.7 mm; 5) impact-resistant polystyrene (sheet) target, ball diameter 1.5 mm. σ, C m^{-2}; S_C, m^2.

On disruption (separation) of the contact surfaces an electrical field arises in the gap. For a given field strength, determined by the dielectric properties of the gaseous medium and the shape of the two surfaces, there is a gas discharge in the gap between the surfaces, sharply increasing the ionic concentration. The ions formed under the action of the electric field are adsorbed on the charged surfaces and the surface charges are reduced.

The experimental apparatus used is shown in Fig. 2. The apparatus [3] consists of a pneumatic tube 1, in which metal balls are accelerated by an air jet. On reaching the target 3, the balls acquire an electric charge. The charged balls arrive at the electrode 4, are discharged, and fall into a bin. Balls of diameter 1.67-3.7 mm were used.

The conditions of contact between the metal ball and the target were varied in the experiment, and the velocity of the ball varied between 1.6 and 8.3 m/sec.

The charge of the ball was determined from the area of the oscillogram obtained on contact with electrode 4. The electric-charge density at the contact was determined as the ratio between the charge of the ball and the contact area.

The contact area is found by a method used in electrophotography [5]. The area charged in the contact between the ball and the target forms a latent image, which is shown up by electrographic power and photographed through a microscope.

Experimental data in the form of the mathematical expectation of the electric-charge density formed in the contact between the ball and the target are shown in Fig. 3. For small contact areas (less than 10^{-6} m^2) the charge density is approximately an order of magnitude larger than for larger surfaces. This is because sparking of the gas discharge in the gap between the two surfaces is difficult if the contact area and hence the volume occupied by the electric field are small. In this case the charge density is determined by spontaneous electron emission due to the strong electric field in the gap [1, 3, 5].

For contact surfaces larger than 10^{-6} m^2, charge dissipation is mainly due to the gas discharge occurring in the gap.

For comparison, Fig. 3 shows the limiting electric-charge density (dashed line) calculated for an electric-field strength of $30 \cdot 10^5$ V/m for air.

Both in the region of spontaneous electron emission (contact area less than 10^{-6} m^2) and in the gas-discharge region (contact area more than 10^{-6} m^2), the density of ions forming in the gap is independent of the rate separation of the contact surfaces. This agrees with the physical model developed for the adhesion of solids [1].

It may be shown that the physical model developed for charging may also be used for a flux of dielectric particles moving in restricted conditions. Because of turbulent inhomogeneity, the particles move from the flow core to the wall, collide with the wall, acquire an electric charge, and return to the flow core. Because of the collision the particle loses some of the energy that sustains the flow; there is a continuous dissipation of energy from the flow core at the wall. One of the spectral components of the energy lost by the flow is the electrical energy leading to the appearance of charging currents in the wall–ground circuit. Charge transfer from the wall to the flow core occurs until electrostatic equilibrium is established, until the flow core has the equilibrium electric charge for the given electrostatic conditions.

In turn, the increase in charge of the flow core leads to increase in particle concentration in the layer at the wall and to change in the hydrodynamic flow parameters. In this case the two-phase flow is identical with the so-called electric current of the flow. The electric charge carriers in this case are particles charged as a result of contact with the wall.

In solving this problem it is assumed that the particle size is much less than the characteristic dimension of the system, that the particles are spherical, and that they move in the flow with the mean (over the cross section) velocity. The single-component approximation is considered; i.e., it is assumed that the particles carry a charge of a single sign.

According to charge conservation, the current density in the flow and the bulk charge density of the flow are related by the equations

$$\operatorname{div} j_F = -\frac{\partial q_F}{\partial \tau}, \tag{11}$$

$$j_F = \gamma E + q_F v. \tag{12}$$

Taking into account Eq. (12) in the conservation equation gives

$$\operatorname{div}(\gamma E) + \operatorname{div}(q_F v) + \frac{\partial q_F}{\partial \tau} = 0. \tag{13}$$

Since $q_F = \operatorname{div}(\varepsilon_0 E)$ and $\partial q_F/\partial \tau = 0$, Eq. (13) takes the following form for steady conditions of motion:

$$\operatorname{div}(\gamma E) + \operatorname{div}(q_F v) = 0. \tag{14}$$

For a two-phase flow with a disperse medium of low electrical conductivity ($\gamma \to 0$)

$$\operatorname{div}(q_F v) = 0. \tag{15}$$

For nonsteady conditions of motion ($\partial q_F/\partial \tau \neq 0$), Eq. (13) may be written for the case $\gamma \to 0$ in the form

$$\operatorname{div} j_F = -\operatorname{div}(q_F v). \tag{16}$$

Since $I_c = I_F$, Eq. (16) leads to an expression for the charging current:

$$I_c = \operatorname{div} j_F \, dV = \operatorname{div}(q_F v)\, dV. \tag{17}$$

For steady motion, taking into account Eq. (14), the charging current density $j_F = 0$.

The motion of the two-phase flow occurs in conditions of electrostatic equilibrium and the perturbations introduced in the flow lead to an electrical reaction of the flow, tending to return it to the equilibrium state. If the perturbations lead to increase in the bulk charge, the flow will lose charge. The amount of charge lost, leading to discharge currents, is determined by the difference between the equilibrium charges before and after the introduction of the perturbation in the flow. Conversely, if the perturbations lead to decrease in the bulk charge, the flow acquires charges as a result of the triboelectric effect. In these conditions a charging current is observed.

The process is self-regulating, so that the electric charge retained by the particle after separation of the contact surfaces is determined by the electric strength of the gaseous medium. The electric-field strength of the gaseous medium in the gap corresponds to the limiting electric-charge density on the surfaces after separation (σ_{lim}).

The limiting charge density on the surface of a particle moving in the flow is equal to the density of the bound charges and the charge acquired by the particle as a result of contact with the wall

$$\sigma_{lim} = \sigma_E + \sigma. \tag{18}$$

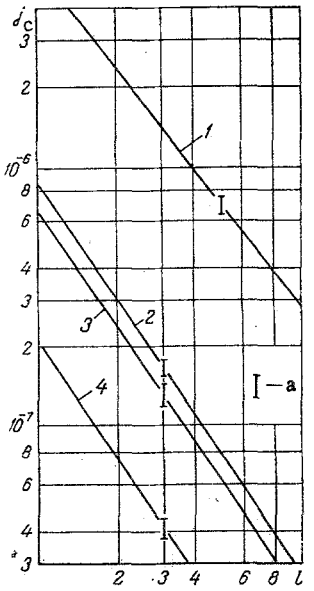

Fig. 4. Charging current density for the acceleration section of horizontal tube in the pneumotransport of granulated polypropylene: 1) air velocity 30.5 m·sec^{-1}; disperse phase, granulated polypropylene ($d_P = 3.3 \cdot 10^{-3}$ m), viniplast tube; 2, 3, 4) air velocity 17.4, 12.9, 12.6 m·sec^{-1}, bulk flow rate coefficient $1.08 \cdot 10^{-3}$, $1.05 \cdot 10^{-3}$, $0.6 \cdot 10^{-3}$, respectively; disperse phase granulated polypropylene, organic-glass tube; a) experimental data.

For a flow bounded by a cylindrical wall of radius R, the charge density at the contact surfaces after separation, taking into account polarization by the external field, is

$$\sigma = \sigma_{\lim}\left[1 + \frac{3S_P cR(\varepsilon - 1)}{2\varepsilon^*(\varepsilon + 2)}\right]^{-1}, \tag{19}$$

where ε^* is the dielectric permittivity of the two-phase system.

Since $q_F = \sigma S_P c$, the limiting equilibrium bulk charge of the flow is

$$q_F = q_{\lim} S_P c\left[1 + \frac{3RS_P c(\varepsilon - 1)}{2\varepsilon^*(\varepsilon + 2)}\right]^{-1}. \tag{20}$$

From Eqs. (17) and (20) the current density as a result of charging is

$$j_c = \frac{\sigma_{\lim}}{2} RS_P \frac{d}{dx}\left\{vc\left[1 + \frac{RS_P c(\varepsilon - 1)}{2\varepsilon^*(\varepsilon + 2)}\right]^{-1}\right\}. \tag{21}$$

The polarity (the direction of current flow) is determined by the behavior of the function $vc = f(x)$; for a decreasing function the material will acquire a charge (electrical charging currents) and for an increasing function it loses charge (electrical discharge currents).

For numerical calculations the following flow parameters are introduced: $i = v_g/v$, the slip coefficient; $c = im_0/g_P$, the concentration of (countable) solid particles in the flow; $m_0 = G_S/G_g$, the coefficient characterizing the bulk flow rate.

As established experimentally [4], in the acceleration section the slip coefficient is given by the expression

$$i = kx^{-n}, \tag{22}$$

where k and n are empirical coefficients; x is the coordinate measured from the point of inlet of the solid phase. Then Eq. (21) leads to the formula

$$j_C = \frac{\sigma_{\lim} S_P G_m Bnx^{n-1}}{2\pi R g_P (x^n + B)^2}, \tag{23}$$

where

$$B = \frac{3RS_p km_0(\varepsilon - 1)}{2g_p e^*(\varepsilon + 2)}.$$

The slip coefficient has been determined experimentally on horizontal pnemotransport equipment [4] for particles of granulated polypropylene propelled by air in tubes of polymethyl methacrylate, viniplast, and aluminum. The air velocity varied between 30.5 and 12.6 m/sec, and the volume-flow-rate coefficient between $3.38 \cdot 10^{-3}$ and $0.6 \cdot 10^{-3}$. The charging current density was calculated from Eq. (23) using the experimental slip coefficient (Fig. 4). The results are in satisfactory agreement with experimental measurements of the charging current in identical conditions [4].

It is evident from Eq. (23) that the charging current density, characterizing the electric-charge transfer by the two-phase flow is determined by the hydrodynamic flow characteristics and the electrophysical properties of the disperson (gas) medium. The results are correct for contact surfaces of electrical resistance more than 10^5 Ω.

NOTATION

σ, electric-charge density; S_C, area of contact surface; E, electric-field strength; E_G, electric-field strength in the gap between the surfaces; r_S, radius of contact surfaces; γ, electrical conductivity of contact surface; v_0, separation rate of contact surfaces; ε, relative dielectric permittivity of particle material; ε_0, dielectric permittivity in vacuum; e, unit electric charge; z, number of unit electric charges in the flow; n(V), bulk concentration of ions in gap between surfaces j_F, current density of flow (flow current referred to cross-sectional area); q_F, bulk charge density of flow; v, mean charged-particle velocity taken over the cross section; I_C, charging current; I_F, flow current; j_C, charging current density (charging current referred to wall surface); σ_E, charge density due to polarization of particles by external electric field; v_g, current velocity (gas velocity); G_g, G_S, bulk flow rate of gas and solid medium; g_p, particle volume; l, tube length.

LITERATURE CITED

1. B. V. Deryagin and N. A. Krotova, Adhesion of Solids [in Russian], Nauka, Moscow (1973).
2. B. G. Popov, V. N. Verevkin, V. A. Bondar' and V. N. Gorshkov, Static Electricity in the Chemical Industry [in Russian], Khimiya, Leningrad (1971).
3. V. N. Baklygin, Author's Abstract of Candidate's Dissertation, Moscow (1972).
4. V. I. Gorshkov, Author's Abstract of Candidate's Dissertation, Moscow (1968).
5. R. M. Schaffert, Electrophotography, Focal Press, London (1975).
6. V. I. Gorshkov, B. G. Popov, and V. N. Verevkin, Teor. Osn. Khim. Tekhnol., 11, No. 6 (1968).