Control of Particle Tribocharging†

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Abstract

When two different materials are brought into contact and separated, an electrical charge is transferred from one to the other. This phenomenon is called contact electrification, contact charging, or tribocharging. Charged particles cause various secondary phenomena during powder processing, such as deposition, adhesion, and electrostatic discharge. Additionally, charged particles are used in many industrial applications such as electrophotography, electrostatic powder coating, and separation; thus, particle charge control is very important for improving particle performance. However, there are still many unknown effects, and in some cases, inconsistent results have been reported. In this review, the basic concepts and theories of charge transfer between solid surfaces are summarized and a description of particle charging caused by repeated impacts on a wall is formulated. On the basis of these concepts and formulations, novel methods of controlling particle tribocharging are presented. In particular, a method using an applied electric field is expected to be applicable in industrial fields.

Keywords: Electrostatics, Tribocharging, Particle electrification, Charge control, Electric field

1. Introduction

Powders and particulate solids are widely used in industry. When handled in air, their surfaces become triboelectrically charged and several other phenomena occur. For instance, in pneumatic transport lines and fluidized beds, particles become charged and adhere to the walls. If the particles are excessively charged, an electrostatic discharge will occur, which can cause fire and explosion hazards. Additionally, electrostatic forces can control the motion of charged particles; thus, many applications have been developed, e.g., electrophotography, electrostatic powder coating, electrostatic precipitation, particle separation, and the construction of electromechanical valves for solids. Moreover, the charge on particles can provide useful information regarding the state of various processes, e.g., powder flow rate, concentration distribution, and several others.

The contact charging and electromechanics of particles have been studied for many years; however, there are still many unknown effects, and in some cases, inconsistent results have been reported. This lack of reliable information is due to the many relevant factors, such as chemical, physical, and electrical properties and environmental conditions, all of which affect the process. To analyze and control particle charging, the measurement of electrostatic charge and the evaluation of electrostatic characteristics are important. To improve existing processes and to develop new applications, it is necessary to obtain an in-depth understanding of these qualities based on theoretical analyses.

In the present review, the basic concepts and theories of charge transfer between solid surfaces are summarized and a model of particle charging caused by repeated impacts on a wall is formulated. On the basis of these concepts and the results of the formulation, new methods for the control of particle tribocharging are presented.
2. Basic Concepts of Contact Electrification

When two different materials are brought into contact and separated, an electric charge is usually transferred from one to the other. This phenomenon is called “contact electrification” or “contact charging.” When they are rubbed, the phenomenon of “tribocharging” or “frictional electrification” occurs. Similarly, short-term contact results in “impact charging.” Contact electrification can also be classified into three categories according to the contacting materials: metal–metal contact, metal–insulator contact, and insulator–insulator contact.

The contact electrification of metals usually goes unnoticed because the transferred charge moves away from the contact point because of the conductivity of the materials. However, when the metals are isolated (electrically) after the contact, the transferred charge can be measured. This transfer of charge is explained in terms of electron transfer arising from the difference in the work functions of the two surfaces. Assuming that electron transfer takes place by tunneling (so that the thermodynamic equilibrium is maintained), the contact potential difference $V_c$ is given by

$$V_c = V_{1/2} = -\frac{(\phi_1 - \phi_2)}{e}$$  \hspace{1cm} (1)

where $V_{1/2}$ is the contact potential difference between metal 1 and metal 2, $\phi_1$ and $\phi_2$ are the work functions of the surfaces, and $e$ is the elementary charge. The amount of charge transferred is equal to the product of the contact potential difference $V_c$ and the capacitance $C$ between the two bodies. The capacitance depends on the state of the contacting surfaces. Although the position of the electrons may vary after the metals are separated, the net charge transferred $\Delta q_c$ can be approximated by the following equation:

$$\Delta q_c = C_0 V_c$$  \hspace{1cm} (2)

The charge transfer in insulator-metal contact can be explained using a model of metal-to-metal electron transfer. This method assumes that an apparent or effective work function can be assigned to the insulator. The amount of charge transferred is determined so as to equalize the energy levels of the two materials. This concept was substantiated experimentally by Davies. Murata and Kittaka, also produced evidence of electron transfer by comparing contact charging experiments to photoelectric emission experiments. The main criticism of the effective work function model is that there are no available free electrons in an insulator. To resolve this situation and to explain the charge transfer for insulator-insulator contacts, several modified models have been developed. Some of these methods are similar to those developed for insulator-metal contact; however, the movement of electrons in the body is more restricted. In one of these models, it is assumed that the energy levels available to the electron are only on the surface, not in the bulk; the available level is called the “surface state.” When insulators come into contact, electrons move from the filled surface states of one insulator to the empty surface states of the other insulator. The driving force for the charge transfer between the surfaces is the difference in the effective work functions of the two surfaces. The charge transfer will cease when the Fermi levels of the two materials are equal.

The physicochemical structure of the surface states is difficult to strictly define. Fabish and Duke proposed a molecular-ion-state model, which assumes that polymers have donor and acceptor states and that charge is carried by electrons. Thus, despite the inclusion of “ion” in the name of the model, it is actually an electron transfer model. In their model, the distribution of the molecular-ion-state is assumed to be a Gaussian distribution. Yanagida et al. calculated the level of the highest occupied molecular orbital (HOMO) of an oligomer using a semi-empirical molecular orbital method. The values calculated using this model were nearly proportional to the measured values of the threshold energy of photoemission, which corresponds to the effective work function of the polymers. This result shows that quantum chemical calculations are applicable to the evaluation of the tribocharging of polymers. Yoshida et al. studied charge transfer in a polymer–metal contact system using another molecular orbital method and paying particular attention to surface defects. When an atom is missing a neighbor to which it would be able to bind, a dangling bond occurs. This kind of defect can be made during frictional contact. Although the number of quantitative analyses remains limited, it is expected that quantum chemical calculations can be used to understand charge transfer between surfaces.

3. Mechanism of Particle Charging

3.1 Condenser model

The contact region between two bodies can be treated as though it were a capacitor. When a particle impacts and rebounds on a wall, the contact


\[ \Delta q = k_c CV \]  

(3)

where \( k_c \) is the charging efficiency, \( C \) is the capacitance, and \( V \) is the total potential difference. The capacitance \( C \) is given by

\[ C = \frac{\varepsilon_0 S}{z_0} \]  

(4)

where \( \varepsilon_0 \) is the absolute permittivity of the gas, \( S \) is the contact area, and \( z_0 \) is the critical gap (which includes the geometrical factors between the contact bodies). The total potential difference \( V \) at the contact gap is given by

\[ V = V_c - V_e - V_b + V_{ex} \]  

(5)

where \( V_c \) is the potential difference based on the surface work functions and \( V_e \) is the potential difference arising from the image charge, which is given by

\[ V_e = k_e q \]  

(6)

where \( q \) is the particle charge held on the particle before contact. \( V_b \) is the potential difference arising from the space charge caused by the surrounding charged particles, and which is given by

\[ V_b = k_b q \]  

(7)

\( V_{ex} \) is the potential difference arising from other electric fields. For instance, an external electric field may be applied to the system. In addition, when the wall is an insulator, the wall surface can retain charge and form an electric field, thus affecting the total potential difference. If the charge accumulates via contact charging, the total potential difference will decrease with increasing surface charge.

\section*{3.2 Charge relaxation model}

Matsuyama and Yamamoto\(^{63, 64}\) proposed another charging model, called the ‘charge relaxation model’. When the two bodies are brought into contact with each other, charge is transferred across the contact gap; however, if the charge transferred to the particle is high enough, relaxation of the transferred charge occurs because of the action of gas discharge during the separation process. To determine the breakdown voltage in the gap, the Paschen curve is applied. This method is widely used in air insulating technology to provide the gas breakdown limit voltage between two parallel electrodes as a function of pressure and gap distance\(^{65}\). The remaining charge depends on the dielectric constant, the particle diameter, and the breakdown voltage of the gas.

\section*{3.3 Impact on a wall}

In powder handling operations, individual particles acquire charge during collisions with the surrounding walls. An understanding of the charging process of a single particle is a basic requirement for the development of a theory of tribocharging of particles\(^{66}\). Several studies have been reported in which a single particle of a few millimeters in diameter was made to collide with a metal target and the transferred charge was measured\(^{65, 64, 67-73}\). Single-particle experiments with a larger sphere (31 mm in diameter) or with a particle as small as 100–300 \( \mu \)m\(^{74}\) were also performed. Watanabe et al.\(^{75-77}\) also constructed a new test rig for small particles with which the initial charge and charge transfer due to a single impact on a target plate could be measured. These methods have several advantages, i.e., the contact state during the particle collision can be reproduced by controlling the impact velocity and angle. The impact charge for a zero initial charge is the characteristic charge; it increases with increasing impact velocity. The effect of impact angle on tribocharging was investigated using an inclined target and a rotating target\(^{78}\). The charge of a particle increases with the impact angle up to 60\(^\circ\) and thereafter decreases. This charging tendency can be explained using a rolling–slipping model. For \( \theta \leq 60\, \text{\degree} \), the effective contact area increases with the angle, because of the increase in the rotation of the particle on the target. For \( \theta > 60\, \text{\degree} \), the effect of the slip on the target increases with the angle; thus, the effective contact area decreases. The effects of contact conditions such as contact time and contact area on particle charging were investigated by Ireland\(^{79, 80}\).

\section*{3.4 Repeated impacts of a single particle}

When a particle repeatedly collides with a wall, the charge on the particle varies according to the electrostatic properties and the state of the collisions. To begin the analysis of successive impact charging, single-particle experiments were carried out using two metal targets, showing that the charge generated by the first impact affects subsequent instances of impact charging\(^{79}\).

Repeated impact tests to study the charge accumulation were carried out by Matsusaka et al.\(^{61}\). To control the contact area easily, a large sphere (made of synthetic rubber) was used. The transferred charge
caused by an impact decreased with the number of impacts. The accumulated charge approached a limiting value, which tended to decrease as the time interval between impacts increased. This was because the leakage of the electrostatic charge increased with increasing elapsed time.

It is possible to determine the particle charge generated by repeated impacts. First, the condenser model is applied to this formulation. To obtain the charge \( q \) as a function of the number of collisions \( n \), a continuous quantity \( dq_c/dn \) is used, i.e.,

\[
\frac{dq_c}{dn} = k_c CV
\]  

(8)

The leakage of electrostatic charge \( dq_e/dt \) is approximated by

\[
\frac{dq_e}{dt} = -k_e q
\]  

(9)

where \( k_e \) is a constant. If the frequency of particle collisions is defined as \( f \), Eq. (9) can be rewritten as

\[
\frac{dq_e}{dn} = -k_e f q
\]  

(10)

From the above equations, the net charge transfer is given by

\[
\frac{dq}{dn} = \frac{dq_c}{dn} + \frac{dq_e}{dn}
\]  

(11)

Solving Eq. (11) with initial conditions \( n = 0 \) and \( q = q_0 \), one arrives at the following exponential equation:

\[
q = q_0 \exp \left( -\frac{n}{n_0} \right) + q_\infty \left( 1 - \exp \left( -\frac{n}{n_0} \right) \right)
\]  

(12)

where \( n_0 \) is the relaxation number and \( q_\infty \) is the equilibrium charge.

It should be noted that an equation of the same form as Eq. (12) can also be derived from the charge relaxation model from the phenomenological level. The charge relaxation model and the condenser model have certain differences. In the condenser model, \( q_\infty \) is proportional to the contact potential difference \( V_c \); whereas, in the charge relaxation model, \( q_\infty \) is independent of \( V_c \).

3.5 Particle charging in gas–solids pipe flow

In gas–solids pipe flow, particles repeatedly collide with the inner wall causing charge transfer\(^{31} \). When a metal pipe is grounded, the charge transferred from the particles to the walls flows to ground, and can be detected as an electric current\(^{21, 82, 88} \).

When the effect of particle–particle interactions on particle charging is negligible in dilute-phase gas–solids pipe flows, each particle can freely collide with the inner wall. Under these conditions, the electric current is proportional to the mass flow rate of particles. For dense-phase gas–solids pipe flows, the surrounding particles prevent free particle–wall contact, and consequently, the efficiency of the charge transfer is reduced. For smaller particles, the efficiency decreases because of agglomeration. In addition, the initial charge on particles affects the electric current. In powder handling operations, particles collide with different walls before arriving at the current detection pipe, e.g., hopper, feeder, chute, disperser, etc., and thus, the polarity and amount of charge on particles varies according to experimental conditions.

To estimate the charge transferred from the particles to the wall, the initial charge must be known beforehand.

Particle charging in gas–solids pipe flow can be formulated as follows. When a particle moves from \( x \) to \( x + \Delta x \) along the pipe axis, the variation of the charge can be derived from Eq. (12) as follows:

\[
\Delta q = q(x + \Delta x) - q(x) = (q_\infty - q_0) \left\{ \exp \left( -\frac{n(x)}{n_0} \right) \right\} 1 - \exp \left( -\frac{n(\Delta x)}{n_0} \right)
\]  

(13)

The charges transferred from the particles to the pipe wall can be analyzed in terms of electric currents. When some length \( \Delta x \) is isolated electrically and grounded, the electric current \( I \) flowing to ground is expressed as\(^{21} \)

\[
I = \frac{\Delta q}{m_p}
\]  

\[
= (q_{\infty} - q_0) \left\{ \exp \left( -\frac{n(x)}{n_0} \right) \right\} 1 - \exp \left( -\frac{n(\Delta x)}{n_0} \right)
\]  

(14)

where \( W_p \) is the mass flow rate of particles, \( m_p \) is the mass of the particle, \( q_\infty \) and \( q_0 \) are the specific charge at \( x = 0 \) and \( x = \infty \), respectively. When the point \( x \) at the inlet of the detection pipe is redefined as zero, Eq. (14) becomes

\[
I = (q_{\infty} - q_0) \left\{ 1 - \exp \left( -\frac{n(\Delta x)}{n_0} \right) \right\}
\]  

(15)

Furthermore, Eq. (15) is rewritten as

\[
I = a(q_{\infty} - q_0) + b
\]  

(16)

where, \( a \) and \( b \) are constants. Using Eq. (16), one finds that the transferred charge is proportional to the initial charge on the particles.
The above theoretical approach can be used to analyze the charge distribution. Although the particle charge distribution depends on manifold factors, the primary factors are considered to be the number of particle collisions, the initial charge on the particles, and the state of the impact. Introducing the probability density functions for these factors, one can obtain the equation of particle charge distribution\(^{30}\).

The maximum (or the equilibrium) charge of particles in gas–solids pipe flow was studied by Matsuyama and Yamamoto\(^{30}\). They conducted a theoretical calculation based on the charge relaxation model, taking into account the space charge effect and made comparisons with the experimental data in the literature.

### 3.6 Control of tribocharging

In general, the reproducibility of the tribocharging of particles is poor; however, the control of the charge on particles can be made possible by employing the tribocharging principles. In this section, typical triboelectric characteristics in dilute phase gas–solids flow is described and useful methods for controlling tribocharging are explained.

Matsusaka et al.\(^{91}\) conducted experiments on the tribocharging of micrometer-sized alumina particles in gas–solids pipe flow using different kinds of pipes. The particles were charged positively by being placed in contact with the stainless steel walls. As for the aluminum, copper, and brass pipes, the particles were charged negatively. Although the absolute value of the specific charge increased with increasing pipe length, the rate of increase gradually decreased and the specific charge approached an equilibrium value that depended on the wall material. To apply the theoretical model to the experimental results, one can assume that the frequency of the particle-wall impacts per unit pipe length is constant, i.e., the number of impacts \(n\) is proportional to the pipe length \(L\); therefore, Eq. (12) can be rewritten as

\[
q_m(L) = q_{m0} \exp\left(\frac{L}{L_0}\right) + q_{m\infty}\left(1 - \exp\left(-\frac{L}{L_0}\right)\right)
\]  

(17)

where \(L_0\) is the characteristic length of the particle charging. This equation can also be used to evaluate the particle charging efficiency \(\gamma_q\), i.e.,

\[
\gamma_q = \frac{q_m - q_{m0}}{q_{m\infty} - q_{m0}} = 1 - \exp\left(-\frac{L}{L_0}\right)
\]  

(18)

The effect of the initial charge on particles and pipe material on particle charging is shown in Fig. 1\(^{91}\). As the experimental results are in good agreement with the results calculated using Eq. (17), the tribocharging of particles can accurately be estimated; moreover, a particle charging control system made of two different materials A and B can be realized. Fig. 2 illustrates a model of the control system in which two different pipes (of length \(\Delta L_A\) and \(\Delta L_B\)) are arranged in series. The specific charges of the particles \(q_{mA}\) and \(q_{mB}\) after making contact with A and B, respectively, in the \(k\)-th component are represented by the following recurrence relations:

\[
q_{mA} = q_{mA-1}\exp\left(-\frac{\Delta L_A}{L_{A0}}\right)
\]

\[
+ q_{mA\infty}\left(1 - \exp\left(-\frac{\Delta L_A}{L_{A0}}\right)\right)
\]

(19)

and

\[
q_{mB} = q_{mA}\exp\left(-\frac{\Delta L_B}{L_{B0}}\right)
\]

\[
+ q_{mB\infty}\left(1 - \exp\left(-\frac{\Delta L_B}{L_{B0}}\right)\right)
\]

(20)

where \(q_{mA\infty}\) and \(q_{mB\infty}\) are the equilibrium specific charges, and \(L_{A0}\) and \(L_{B0}\) are the characteristic lengths for contact with pipe material A and B, respectively.

![Fig. 1](image1.png)  
Effect of initial charge and pipe material on particle charging (alumina particles, count median diameter: 3.3 μm, pipe diameter: 6 mm, air velocity: 40 m/s, mass flow ratio: 5 × 10^{-4} kg-particle/kg-air).

![Fig. 2](image2.png)  
A model of a particle charging control system made of two different materials, A and B.
The result for the specific charge obtained by connecting 1-m brass pipe and 1-m stainless steel pipe alternately is shown in Fig. 3\(^{[91]}\). The particles are charged, negatively in the brass pipes, and positively in the stainless steel pipes. As a result, the values of the specific charge are within a certain range. The experimental results can be represented by Eqs. (19) and (20).

Examples of the general calculation to control tribocharging in gas-solids pipe flow using two different pipe materials A and B are shown in Fig. 4. Although the charge fluctuates positively and negatively, the fluctuation level decreases with the decrease in the individual pipe lengths. The polarity and amount of charge is controlled by changing the pipe length ratio, i.e., \( r_A = \Delta L_A / (\Delta L_A + \Delta L_B) \) or \( r_B = \Delta L_B / (\Delta L_A + \Delta L_B) = 1 - r_A \). Therefore, the charge on particles can be changed positively, negatively, or neutrally using two different materials.

The recurrence relation mentioned above can be solved as follows:

\[
q_{mB} = q_{m0} \exp \left(-\frac{L_k}{L_{AB0}}\right) + q_{mB}^* \left\{1 - \exp \left(-\frac{L_k}{L_{AB0}}\right)\right\} (21)
\]

where

\[
q_{mB}^* = q_{mA\infty} \left\{1 - \frac{1 - \exp \left(-\frac{r_B \Delta L}{L_{AB0}}\right)}{1 - \exp \left(-\frac{\Delta L}{L_{AB0}}\right)}\right\}
+ q_{mB\infty} \left\{1 - \exp \left(-\frac{\Delta L}{L_{AB0}}\right)\right\} (22)
\]

and

\[
L_{AB0} = \frac{L_{A0}L_{B0}}{r_B L_{A0} + r_A L_{B0}} (23)
\]

When the pipe length \( \Delta L_A \to 0 \), the specific charge is expressed as a continuous function, i.e.,

\[
q_m = q_{m0} \exp \left(-\frac{L}{L_{AB0}}\right) + q_m^* \left\{1 - \exp \left(-\frac{L}{L_{AB0}}\right)\right\} (24)
\]

where

\[
q_m^* = q_{mA\infty} \left\{1 - \frac{r_B L_{AB0}}{L_{B0}}\right\} + q_{mB\infty} \frac{r_B L_{AB0}}{L_{B0}} \]

\[
= \frac{q_{mA\infty} r_A L_{B0} + q_{mB\infty} r_B L_{A0}}{r_B L_{A0} + r_A L_{B0}} (25)
\]

This system can be arranged in different shapes and structures. Fig. 5 shows a high-efficiency particle charger with an inverted, truncated cone\(^{[92]}\). Micrometer-sized dielectric particles that are introduced into the charger from the tangential direction at the top are carried spirally downward and discharged in the tangential direction at the bottom. The particles are triboelectrically charged by contact with the inside wall of the charger via centrifugal force. When two different metals, A and B, are affixed to the inside wall, particles will make contact with these materials alternately. Fig. 6 shows an example of...
the experimental results obtained using the particle charger. The charge on particles is estimated theoretically and can be controlled by changing the area fraction of the wall materials. The charge control range is determined by the two contact potential differences between the particles and the two walls, \( A \) and \( B \).

Furthermore, when applying an external electric field to the system, the contact potential difference can easily be changed; as a result, the charge control range becomes wider. Fig. 7 shows the concept of particle charge control based on contact potential difference. The contact potential difference \( V \) consists of the four factors, as expressed in Eq. (5), i.e., \( V_e \) based on the surface work functions, \( V_c \) arising from the image charge, \( V_a \) arising from the space charge, and \( V_n \) arising from an applied electric field. Therefore, in the case of \( V < 0 \) the particles are negatively charged, and for \( V > 0 \) they are positively charged. In addition, the amount of charge on the particles can be controlled by varying the contact potential \( V \). A particle charger using an applied electric field system is shown in Fig. 8. This charger is also based on the centrifugal contact method. When two different voltages are applied, particle charging is similar to that using two different materials, as shown in Fig. 6. Particle charging control based on contact potential difference in an applied electric field is easier and safer than corona discharge methods. In addition, the device can be customized to meet the needs of each application. Therefore, this control method is expected to be applicable in many industrial fields.

4. Conclusion

As described in this review, much research on particle tribocharging has been carried out over the last several decades. Although there are still unknown effects in the mechanism of tribocharging, the charge accumulation on particles can be formulated in terms of electron transfer. Tribocharging depends on the contact potential difference, which can be controlled via an applied electric field or by controlling the materials of the apparatus; therefore, particle charging can be estimated theoretically using these factors. In addition, as the particle charging is a surface phenomenon related to the contact between two bodies, the contact efficiency is also important when analyzing the particle charging process.

In this review, to control the charge on particles, novel methods based on applied electric fields (to control the contact potential difference) and centrifugal force (to enhance the contact efficiency) have been presented. These methods, which are both easy and safe, can be designed so as to meet the needs of different situations, and thus, are expected to be applicable in many industrial fields.

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Fig. 7 Conceptual model of particle charge control based on contact potential difference \( V = V_c - V_e - V_b \), \( V_c < 0 \), see Eq. (5)).

Fig. 8 Particle charger using centrifugal contact in an electric field system.
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