Advanced Powder Technology 26 (2015) 454–461

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Advanced characterization of particles triboelectrically charged by a two-stage system with vibrations and external electric fields

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ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 12 November 2014
Accepted 30 November 2014
Available online 11 December 2014

Keywords:
Particle tribocharging
Repeated contact
Vibration
Electric field
Initial charge

ABSTRACT

In this study, we propose a new method to effectively characterize particle tribocharging caused by repeated contact with a wall in an external electric field. We perform experiments using a two-stage system consisting of two inclined vibrating plates and electrodes. The mass flow rate and charge of particles were controlled at the first vibrating plate, and the charge that was transferred from the plate to the particles was obtained from the difference between the charges on particles at the lower and upper ends of the second vibrating plate. In addition, electric currents generated by the charge transfer were simultaneously measured at the second vibrating plate. From these measurements, we verified that the charge balance in this system holds. Furthermore, we found that the charge transfer depends on various factors, such as the initial charge, chemical and electrical properties, travel length of particles, and the external electric field. We also found that the equilibrium charge of particles depends on the chemical property and external electric field. The equilibrium charge and the rate of tribocharging were evaluated analytically from the relationship between the initial and transferred charges without changing the travel distance of particles. This method enables the rapid and reliable analysis of the particle tribocharging process.

1. Introduction

When two different materials are brought into contact with each other, an electric charge is transferred from one to the other. This phenomenon is called “contact electrification” or “contact charging.” When they are rubbed against each other, it is called “triboelectric charging,” or simply “tribocharging.” With respect to brief contact made during collisions, it can be called “impact charging” [1,2]. In practice, it is not easy to classify the contact states into groups, such as sliding, rolling, and impact; thus, the term “tribocharging” is used in such general cases. If the materials are insulators, charges remain on the surfaces. As a result, the electrostatic phenomena that occur with solid particles are significant as the specific surface area increases. For example, electrostatic forces acting on charged particles affect powder flowability [3–7] and segregation [8]. In addition, excessively charged particles cause an electrostatic discharge, which can pose the risk of fire and explosion hazards [9]. On the other hand, charged particles can be used for many industrial applications, including electrophotography [10], electrostatic powder coating [11], electrostatic separation [12,13], self-assembly [14], and various measurements [15–17].

In industry, the characterization and control of particle tribocharging are essential to maintain powder processes in normal operating conditions, and to maximize the performance of various pieces of equipment. The cascade method to measure the charge of particles cascading down an inclined plate has often been used for characterizing particle tribocharging because of its ease of operation [18–20]. However, the motion of small particles that are on the surface is disturbed by adhesive forces such as van der Waals forces [21] and electrostatic forces [22–25]. To overcome these adhesive forces, external forces should be applied continuously [26,27]. For example, particles have been charged by repeated contact on a vibrating feeder [28] or in a shaker [29,30]. Otherwise, particles have been charged in gas-solid pipe flows without using vibration [31], and the frequency of particle–wall contacts may be increased by applying a centrifugal force to the particles in a rotational flow [32–34]. Furthermore, because particle tribocharging is affected not only by the material property but also by the electric field [35], the charges on the particles can be altered by changing the electric field.

In one study, the authors expanded the range of the particle charge and improved the controllability by applying an external electric field to the particle tribocharging caused by repeated contact under vibration [36], and they also proposed a two-stage system with a pre-charging stage for controlling the initial charge

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http://dx.doi.org/10.1016/j.apt.2014.11.021

Nomenclature

a	slope of linear function (–)
b	y-intercept of a linear equation (C/kg)
C	capacitance between contact surfaces (F)
D_p	particle diameter (m)
D_{p50}	count median diameter of particles (m)
d	average bounce distance (m)
E_{ex}	electric field (V/m)
E_{ex0}	electric field for $q_{m\infty} = 0$ (V/m)
I	electric current (A)
k_b	constant in Eq. (3) (1/F)
k_c	constant in Eq. (5), i.e., charging efficiency (–)
k_e	constant in Eq. (2) (1/F)
k_{ex}	constant in Eq. (4) (–)
L	length of electrode or travel distance of particles (m)
L_0	characteristic length of particle tribocharging (m)
M_t	total mass of particles (kg)
m_p	mass of a particle (kg)
n	number of particle-wall contacts (–)
n_0	characteristic number of particle tribocharging (–)
q	charge on a particle (C)
q_m	specific charge, i.e., charge-to-mass ratio (C/kg)
Δq_m	transferred specific charge (C/kg)
q_{m0}	initial specific charge (C/kg)
$q_{m\infty}$	equilibrium specific charge (C/kg)
q_0	initial charge of a particle (C)
q_∞	equilibrium charge of a particle (C)
t	time (s)
V	total potential difference (V)
V_b	potential difference arising from space charge (V)
V_c	contact potential difference based on surface work functions (V)
V_e	potential difference arising from image charge (V)
V_{ex}	potential difference arising from external electric field (V)
w_p	mass flow rate of particles (kg/s)
y	displacement of vibration (m)
z_0	critical gap between contact surfaces (m)

Greek letters

ε_0	absolute permittivity of gas (F/m)
ρ_e	volume resistivity (Ω m)
ρ_p	particle density (kg/m^3)
σ_g	geometric standard deviation of particle diameter (–)

and mass flow rate of particles [37]. In this system, the particle tribocharging was analyzed by measuring the charge on particles using a Faraday cup. If electric currents are measured online, the procedure will be simplified and the analysis will be more flexible.

In this study, we modify the two-stage system used to characterize particle tribocharging in order to measure electric currents as well as particle charges, and then evaluate the performance of the modified system. Next, we analyze in more detail the equilibrium charge of particles and the rate of tribocharging to better understand the particle tribocharging caused by repeated contact. Finally, we propose a new method to characterize the particle tribocharging on the basis of the theoretical analysis taking into account the initial charge of particles and the external electric field.

2. Theoretical model

2.1. Basic concept of particle tribocharging caused by repeated contact

The theoretical model of the particle tribocharging has been reported elsewhere [1,2,33]. Here, we describe the basic concept used to analyze the particle tribocharging caused by repeated contact with a wall in an external electric field. The total potential difference V at the contact gap, which is the driving force for charge transfer, is expressed as

$$V = V_c - V_e - V_b + V_{ex}, \tag{1}$$

where

$$V_e = k_e q, \tag{2}$$

$$V_b = k_b q, \tag{3}$$

and

$$V_{ex} = k_{ex} z_0 E_{ex}, \tag{4}$$

where V_c is the potential difference based on the surface work functions, and V_e and V_b are the potential differences arising from the image charge and the space charge caused by the surrounding charged particles, respectively, which act as an inhibitor for the particle tribocharging caused by repeated contact. k_e and k_b are constants, q is the charge on the particle, and V_{ex} is the potential difference arising from the external electric field. V_{ex} does not depend on q, and has the same effect as V_c. When the sum of V_c and V_{ex} has a positive value, the particle tends to acquire a positive charge. k_{ex} is a constant, z_0 is the effective contact gap including the surface roughness, and E_{ex} is the external electric field. When the wall is a positive electrode, E_{ex} in Eq. (4) becomes larger than zero, and the particle is able to acquire a positive charge more easily.

When the charge transferred between the contact surfaces is proportional to both the total potential difference V and the capacitance C, the continuous quantity $\mathrm{d}q/\mathrm{d}n$ is expressed as

$$\frac{\mathrm{d}q}{\mathrm{d}n} = k_c C V, \tag{5}$$

where n is the number of particle-wall contacts and k_c is a constant, i.e., charging efficiency. Assuming that the number of particles is sufficiently small, and thus the space charge is negligible, by solving Eq. (5) with the initial condition $q = q_0$ at $n = 0$, we obtain the following exponential equation:

$$q = q_0 \exp\left(-\frac{n}{n_0}\right) + q_\infty\left\{1 - \exp\left(-\frac{n}{n_0}\right)\right\}, \tag{6}$$

where

$$q_\infty = \frac{V_c + V_{ex}}{k_e} = \frac{V_c + k_{ex} z_0 E_{ex}}{k_e} \tag{7}$$

and

$$n_0 = \frac{1}{k_e k_c C}, \tag{8}$$

where q_∞ is the equilibrium charge of the particle and n_0 is the characteristic number of the particle tribocharging.

2.2. Method for characterizing particle tribocharging caused by repeated contact

When particles are traveling on an inclined vibrating plate, it can be assumed that the frequency of the particle-wall contacts per unit length is constant, and that the number of contacts n is