An Experimental Study of Multi-Particle Dynamics in Triboelectrostatic Systems

Final Technical Report

by

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Abstract

Using state-of-the-art flow/particle visualization and animation techniques, the time-dependent statistical distributions of charged-particle swarms exposed to external fields (both electrostatic and flow) are analyzed. We found that interparticle interaction and drag forces mainly influenced swarm dispersion in a Lagrangian reference frame, whereas the “average” particle trajectory was affected primarily by the external electric field.

1. Introduction

The phenomenon of frictional charging, triboelectrostatics was discovered in ancient times, when a piece of amber would attract small fragments of matter when rubbed with cloth or fur; however, the mechanism by which charge is transferred between substances is still not fully understood. Lowell and Rose-Inness¹ provide an excellent review of the contact electrification of both metals and insulators, covering not only experimental methods in charge measurement, but also the three proposed mechanisms of frictional charging: material, ion, and electron transfer. Experimental studies based on charge density measurements²⁻⁶, including the variability of surface charge density with both chemical surface modification and increased sample purity, reveal that particle size and surface chemistry have a profound effect on the sign and magnitude of the induced charge. Models, which attempt to describe the rate and efficiency of tribocharging and are based primarily on the existence of surface acceptor/donor sites or “states”, have been developed⁷⁻⁹, however these theories have failed to put the final stamp on the essence of frictional charging.

Triboelectrostatics has been applied successfully to the separation of entrained solid particulates¹⁰⁻¹⁵, including Edison’s pioneering experiments¹⁰ in the separation of gold from quartz more than a century ago. Recently, the idea of triboelectrostatic separation has been expanded to include plastics recycling, the recovery of precious metals, and the beneficiation of power plant inlet and flue gas streams to reduce both burner downtime and particulate emissions to the environment. The inherent advantage in using triboelectrostatics for separation is that it is a dry technique, therefore cleaning/dewatering costs are avoided.

The dynamics of entrained solids is of great interest in many areas, and a comprehensive theory that governs the coupling between fluid flows and solid particles remains elusive. It is well known that, when solid particles are entrained in liquids or gases, the particles exert a force on the fluid, and the fluid simultaneously exerts an equal and opposite force on the particles¹⁶⁻¹⁷, according to Newton's 3rd Law. These forces, as well as the voids caused by the displacement of the fluid by solid particles, cause turbulent wakes in the flow. As a consequence of this induced turbulence, the trajectories of the entrained particles may be altered. For concentrated particle systems, these complex hydrodynamic disturbances can only be interpreted from a statistical viewpoint.

Gupta¹⁸ believed that the external electric field force would dominate the drag and inertial forces in a dilute system, and he attempted to describe the particle concentration in a batch separator by diffusion. However, his oversimplified diffusion equation did not explicitly contain an electrostatic field term and failed to qualitatively describe experimental data.

We have analyzed the individual and average trajectories of triboelectrostatically-charged model particle distributions, or "swarms", inside of a wind tunnel. Laser Doppler velocimetry (LDV) was used to measure both the velocity and turbulence intensity of the entrained particles and the wind tunnel sweep gas. We have studied the effects of the externally-applied electric field, sweep gas velocity, particle injection velocity, and particle size on these trajectories and have found that each of these parameters has a significant effect on the separation. The effects of sweep gas velocity and external electric field are demonstrated in this paper. Similar to the Lagrangian reference frame, we follow the trajectory of the "average" particle, and we observe and qualitatively describe the effect of particle-particle interactions on the dynamics of the charged-particle swarms.

2. Experimental

The experimentation was performed at the Particle Flow Analysis Facility (PFAF) at the Federal Energy Technology Center (FETC) located in Bruceton, PA. The PFAF is equipped with a state-of-the-art flow visualization system designed to track particle trajectories, and LDV apparatus that has the ability to measure particle velocities and both sweep gas velocity and turbulence intensity.

The separation zone, housed inside of a high-velocity wind tunnel, consists of a particle feeder, an injection nozzle, and two copper electrodes spaced 10 cm apart, as shown in Fig. 1. The optical train outside of the tunnel, including a 5-Watt argon ion laser

(Spectra Physics), a plano-convex lens, two cylindrical lenses, and a planar mirror, which illuminates the separation zone via a vertical laser sheet, can also be seen. Model particle systems, a combination of polyvinyl alcohol (PVA) particles, solid and hollow glass spheres, and/or silica gel (SG) particles, are fed to a copper pneumatic transport line and entrained in a flow of nitrogen gas. During transport, these particles collide with each other and the walls of the tube and become charged via frictional collisions. The positively-charged PVA and negatively-charged SG particles then flow past an in-line mixer (to enhance particle charging) to the nozzle, where they are injected between the copper electrodes, which support a DC voltage of up to $\pm 25,000$ V. The nozzle is located approximately 3 cm inside the leading edge of the electrodes to avoid the edge effects of the electric field.

Flow visualization data is acquired by a high-resolution digital camera, which sends digitized images of the particles flowing through the vertical laser sheet to a PC equipped with an image-grabber board. The camera is equipped with a zoom lens, and the rate of data acquisition is approximately one image per three seconds. The images are viewed with OPTIMAS[®] software, and a background image for each experiment was recorded and subtracted from the analyzed data. Pixel-by-pixel averaging of individual images is performed to analyze the evolution of the particle distribution through the separation zone, and slices are “cut” through the averaged plumes to extract the particle density distribution data. For each experiment, approximately 40 individual images were averaged. A typical individual image is shown in Fig. 2(a), and the associated “averaged” image with the drawn slices in Fig. 2(b). Note in Fig. 2 that the PVA particle trajectories can be seen easily, but the

SG trajectories are barely seen due to the poor reflective properties of SG; however, the final deposition of SG particles on the top plate is clearly visible and able to be analyzed. It is also important to note that the intensity contribution of the SG particles must be subtracted from slices 1 to 3 (prior the separation plane) in analyzing the pure PVA plume.

Figure 2. (a) Individual and (b) “averaged” images of charged particles in the separation zone.

Study of the behavior of particle distributions resulting from particle-particle interactions is essential in understanding the underlying mechanisms of particle “swarm” dynamics. The combined effect of three statistical distributions: initial velocity at the nozzle exit, particle size, and particle charge, affects how the swarm moves through the separation zone. Therefore, experimentation controlled these factors, as well as the influences of both the sweep gas and external electric field. Our focus on these issues differs from that of previous investigators, because we are more concerned with the fundamentals of the dynamics of particle clusters resulting from particle/flow couplings and interparticle interactions.

LDV was used to calibrate the seeded sweep gas flow in terms of both horizontal and vertical velocity and turbulence intensity. Note that finite turbulence intensity was detected near the nozzle and the electrodes in an otherwise-laminar flow. We then measured particle velocities exiting the nozzle. Figure 3 shows a representative data set of horizontal and vertical velocities using 45-63 μm glass beads, where N is the number of particles with the given velocity. We see that the horizontal velocity profile for this representative run is unimodal

with a mean of 3.472 ± 0.529 m/s, and the vertical velocity profile is bimodal, very slightly skewed to negative values due to gravitational effects, and centered around zero.

Figure 3. (a) Horizontal and (b) vertical particle velocity distributions at the nozzle exit.

Table 1 shows the particle distributions and conditions for four experimental data sets (denoted I-IV). Comparison of I and II illustrates the effect of the wind tunnel sweep velocity (drag force on the particles) on the swarm dynamics, while comparing III and IV examines how the externally-applied electric field influences the trajectories of the charged particles. Note that in I and II, the PVA and SG particles have the same mean diameter ($85 \mu\text{m}$), whereas in III and IV, small PVA particles ($45\text{-}75 \mu\text{m}$ diameter) are mixed with relatively large ($210 \mu\text{m}$ diameter) SG particles.

Table 1. Experimental conditions for representative separations (shaded areas are controlled conditions).

Experiment	Sweep Gas Velocity [m/s]	Particle Injection Velocity [m/s]	External Electric Field Potential [V]	Particle Size/Size Distribution
I	1.058	2.694	$\pm 2.5 \times 10^4$	50 wt %, $85 \mu\text{m}$ SG & PVA
II	2.739	2.694	$\pm 2.5 \times 10^4$	50 wt %, $85 \mu\text{m}$ SG & PVA
III	0.413	3.472	$\pm 2.5 \times 10^4$	10 wt % $210 \mu\text{m}$ SG; $45\text{-}75 \mu\text{m}$ PVA
IV	0.413	3.472	0	10 wt % $210 \mu\text{m}$ SG; $45\text{-}75 \mu\text{m}$ PVA

3. Data Analysis

To illustrate the details of the swarm dynamics effectively, Figs. 3(a)-(j) show 10 animated frames derived from the averaged image of I, shown in Fig. 2(a) and described in Table 1. Note that the slices in the animation are cut at equal intervals along the horizontal axis.

Figure 3. Ten animated frames showing the evolution of the particle density distribution

For each of the experiments given in Table 1, an averaged image was created and slices cut perpendicular to the “average” particle trajectory so that we could analyze the evolution of the particle density distribution. Figure 4 shows the fitted Gaussian curves for slices 2 through 7 from Fig. 2(b). The intensity values given on the vertical axis of the graph in Fig. 4 are proportional to the number density of particles at that point.

Figure 4. Gaussian fits for slices 2 through 7 shown in Fig. 2(b)

Figure 5. Linear relationship between σ and trajectory distance, $|\mathbf{r}_m|$

For the experimental conditions given in Table 1, we have plotted the standard deviation of the fitted Gaussian curves, σ , as a function of “average” particle trajectory distance and have found that the relationship is linear, as shown in Fig. 5. Note the effect that the sweep gas velocity (compare I and II) has on the dispersion of the plume; as the sweep gas velocity is increased, we see that the dispersion of the plume decreases significantly.

4. Conclusions & Discussion

We have examined the time-dependent statistical distributions of charged-particle swarms by using state-of-the-art flow and particle-visualization techniques. By assuming that the particle distributions are Gaussian and adopting a Lagrangian-like viewpoint, we have analyzed the “average” particle trajectory, $\mathbf{r}_m$, and plume dispersion, as shown in Figs. 3-5.

Figure 6. Illustration of “average” particle trajectory, $\mathbf{r}_m$ and swarm dispersion, σ

Figure 6 illustrates the evolution of the swarm density distribution. Qualitatively, $\mathbf{r}_m$ is primarily influenced by the external electric field, whereas σ is primarily affected by drag and interparticle electrostatic forces. The details of a theoretical development will be published elsewhere.

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Appendix

A Study of *Multi-Particle Dynamics in Triboelectrostatic Systems*

Department of Chemical Engineering, Carnegie Mellon University:

- Stephen J. Vinay III (speaker); Myung S. Jhon, Professor; Charles M. Schroeder III

Solid Fuels Division, Federal Energy Technology Center:

- Richard Schehl; Yee Soong; McMahan Gray; Dennis Finseth; Bill Sands

Outline

- Essence of the Problem & Application
- Experimental
 - »A History of Triboelectrostatic Separations
 - »Particle Flow Analysis Facility (PFAF)
 - »Results from the PFAF -- Experimental Results & Animation of Particle Trajectories
- Theoretical
 - »Probability Density Function Approach -- Qualitative Data Interpretation
 - »Concentration Equation
 - »Moment Analysis & Illustration

Essence of the Problem

➤ Single Particle: Particle/Fluid Coupling

➤ Particle “Swarms”: Interparticle Interactions

Energy/Environmental Application

Low-NO_x Burner Systems

Other Triboelectrostatic Applications

Electronic Scrap/
Recovery of Precious
Metals

Chopped Wire
Processing

Recovery of
Precious Metals
from Slags

Polyethylene
Bottle Recycling

Food
Processing/
Purification

Electrophotography/
Graphics

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Triboelectrostatic Separation Principle

1. Pneumatic transport induces charge via frictional (“tribo”) collisions

2. Separation occurs upon injection into a static, high-voltage electric field

Batch Configuration

Continuous Configuration

Thomas Edison's Pioneering Work

(June 14, 1892)

One Century Later...

FETC's Prototype

Ban & Stencel; U. of Kentucky

Particle Flow Analysis Facility (PFAF)

Flow Visualization Components

- **Data Acquisition System**
- **Laser Doppler Velocimetry System**

Typical PFAF Tribo Data

Particle “Swarm” Dynamics (Qualitative Picture)

Image Analysis

- For N “pictures”:
 - » Pixel-by-pixel addition of intensity
 - » Division by N
 - » Subtraction of background

- “Raw” Averaged Image:

Controlled Experiments

Effect of Drag Force

Wind Tunnel: 1.058 m/s
N₂ Flowmeter: 2.694 m/s
Electric Field: +/- $2.5 \cdot 10^4$ V
50 wt. %, 85 μ SG & PVA

1

Wind Tunnel: 2.739 m/s
N₂ Flowmeter: 2.694 m/s
Electric Field: +/- $2.5 \cdot 10^4$ V
50 wt. %, 85 μ SG & PVA

2

Wind Tunnel: 0.413 m/s
N₂ Flowmeter: 3.472 m/s
Electric Field: +/- $2.5 \cdot 10^4$ V
10 wt. % 210 μ SG; 45-75 μ PVA

3

Wind Tunnel: 0.413 m/s
N₂ Flowmeter: 3.472 m/s
Electric Field: 0 V
10 wt. % 210 μ SG; 45-75 μ PVA

4

SG $\longrightarrow$ Silica Gel; PVA $\longrightarrow$ Polyvinyl Alcohol

1

Wind Tunnel: 1.058 m/s

N₂ Flowmeter: 2.694 m/s

Electric Field: +/- 2.5•10⁴ V

50 wt. %, 85μ SG & PVA

1

1

1

1

1

1

1

1

1

1

1

1

Wind Tunnel: 1.058 m/s
N₂ Flowmeter: 2.694 m/s
Electric Field: +/- 2.5•10⁴ V
50 wt. %, 85μ SG & PVA

2

Wind Tunnel: 2.739 m/s

N₂ Flowmeter: 2.694 m/s

Electric Field: +/- $2.5 \cdot 10^4$ V

50 wt. %, 85 μ SG & PVA

2

Wind Tunnel: 2.739 m/s
N₂ Flowmeter: 2.694 m/s
Electric Field: +/- 2.5•10⁴ V
50 wt. %, 85μ SG & PVA

Effect of Drag Force

(Note that $\dot{r}_i \approx v(r_i)$ in (2))

1

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Controlled Experiments

Wind Tunnel: 1.058 m/s
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①

Wind Tunnel: 2.739 m/s
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②

Effect of Electric Field

Wind Tunnel: 0.413 m/s
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③

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Electric Field: 0 V
10 wt. % 210 μ SG; 45-75 μ PVA

④

Effect of Electric Field

3

Wind Tunnel: 0.413 m/s
 N₂ Flowmeter: 3.472 m/s
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 10 wt. % 210 μ SG; 45-75 μ PVA

Wind Tunnel: 0.413 m/s
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4

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Theoretical Modeling

Simplified Version of the PDF Approach

N-Particle System in Frictional Media

Configurational N-Particle Distribution Function

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_i, \mathbf{r}_N; t)$$

Concentration Equation

$$C(\mathbf{r}, t) = \left\langle \sum_{i=1}^N \delta[\mathbf{r} - \mathbf{r}_i(t)] \right\rangle_{\text{average}}$$

$$= \int \cdots \int d^3\mathbf{r}_N \Psi \sum_{i=1}^N \delta[\mathbf{r} - \mathbf{r}_i(t)]$$

Concentration Equation

$$\frac{\partial}{\partial t} C(\mathbf{r}, t) = \left\langle \sum_{i=1}^N \frac{\partial \mathbf{r}_i}{\partial t} \frac{\partial}{\partial \mathbf{r}_i} \delta(\mathbf{r} - \mathbf{r}_i) \right\rangle = -\nabla \bullet \mathbf{J}(\mathbf{r}, t)$$

$$\mathbf{J}(\mathbf{r}, t) \equiv \left\langle \sum_{i=1}^N \dot{\mathbf{r}}_i \delta(\mathbf{r} - \mathbf{r}_i) \right\rangle$$

A rigorous expression for this **FLUX TERM** can be obtained if $\dot{\mathbf{r}}_i$ is given.

Moment Analysis

- Rigorous solution of the concentration equation is difficult.
- We cast the space-dependent concentration into moment form:

$$\Gamma_n \equiv \int \cdots \int d^3\mathbf{r} \, \mathbf{r} \mathbf{r} \cdots \mathbf{r} C(\mathbf{r})$$

“n” of them

n^{th} -rank tensor or n^{th} moment

Illustration of the First Few Moments

Concentration Profiles - Experiment ①

Modeling Summary

- “Average Particle” Trajectory ($\mathbf{r}_m$) is Influenced Primarily by the External Electric Field & Sweep Gas.
- “Swarm” Dispersion (σ^2) is Primarily Influenced by Drag & Interparticle Electrostatic Forces.