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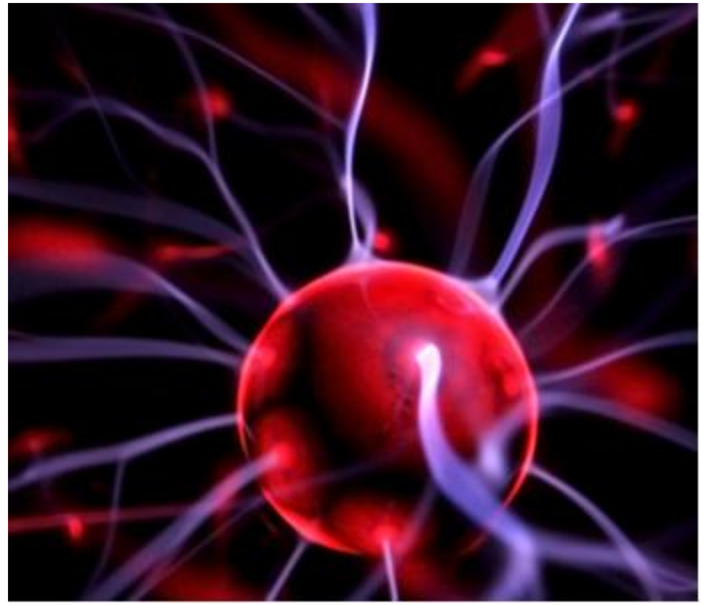
Mechanistic-based multi-scale modeling of tribocharging of powders during pneumatic transport



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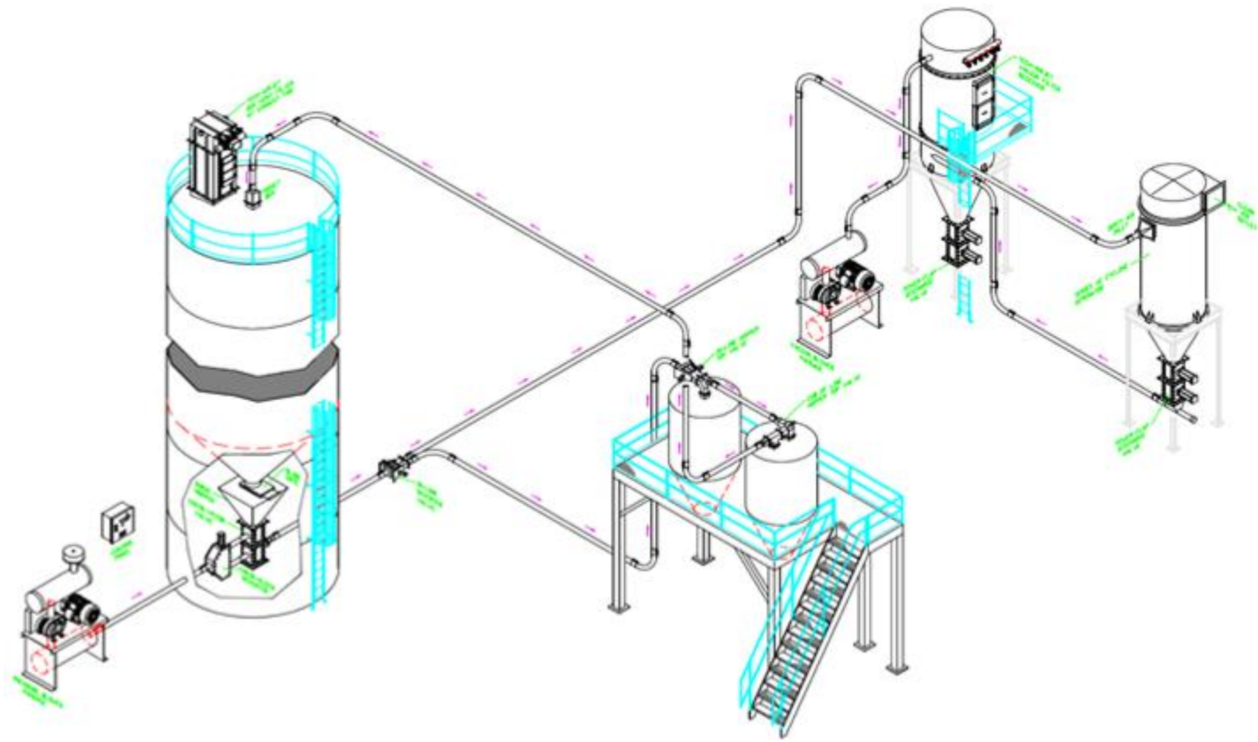
STEP-1
The first small international workshop on Static-Tribo-Electricity of Powder
19th-21st December, 2014

Introduction

Pneumatic Transport (PT) :

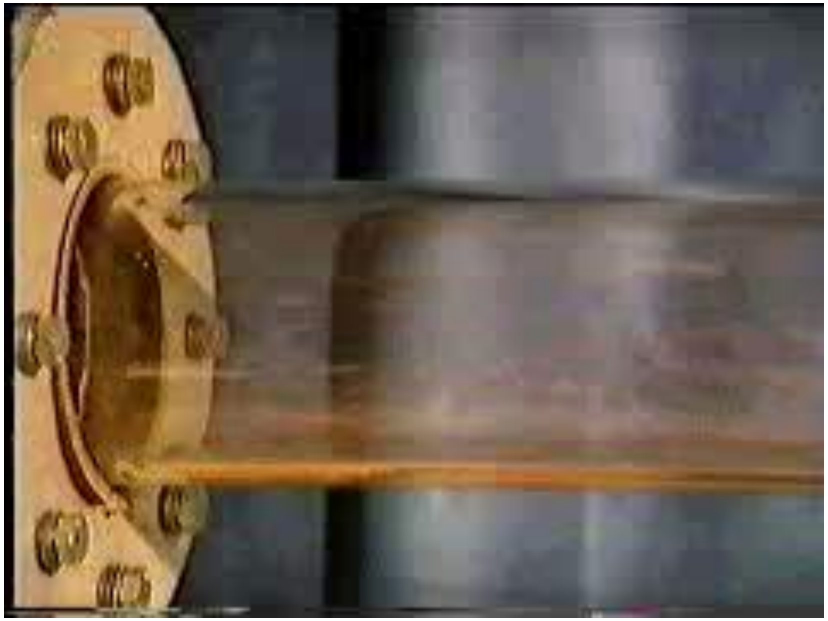
Conveying a bulk material suspended in, or forced by, a gas stream from one point to another through a network of horizontal and/or vertical pipes by compressed air or by vacuum



TYPICAL DILUTE PHASE SYSTEM #2

www.techairinc.com/Prod2PneumaticConv.htm

Transport Regimes



Dilute (lean) phase	Dense phase
Ug : >20 m/s	Ug : 8-15 m/s
Engineering aspects	Low pressure loss/kg of powder
High pressure loss Attrition	Engineering aspects Not always possible

Main Issues

Electrostatic charging & Pneumatic Transport :

- Hazard Concerns

- Pressure loss & energy consumption

- Electrostatic probes for flow measurement

- Pneumatic transport as a tribo-charging test

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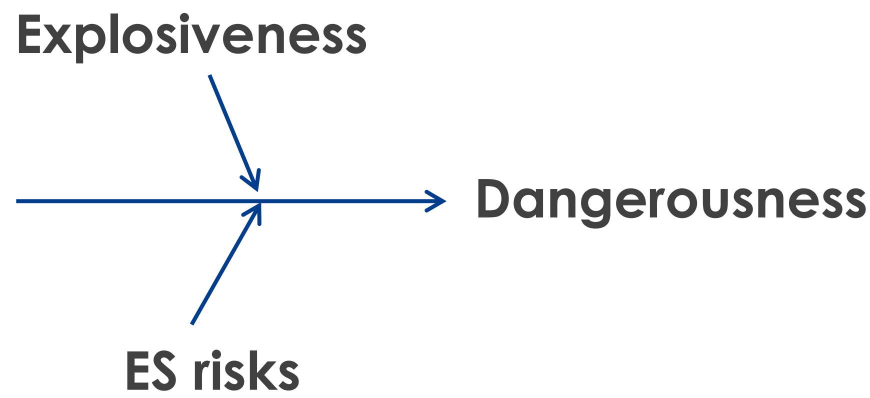
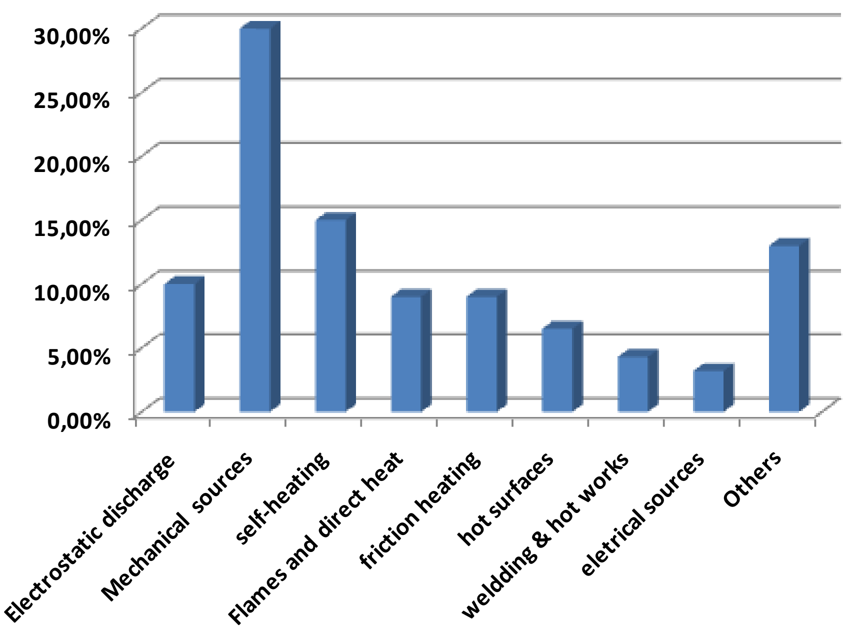
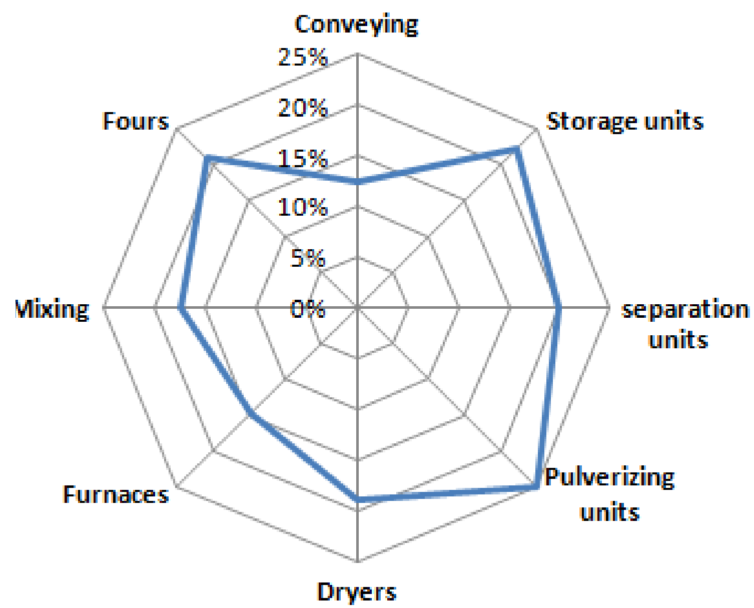
Hazard concerns

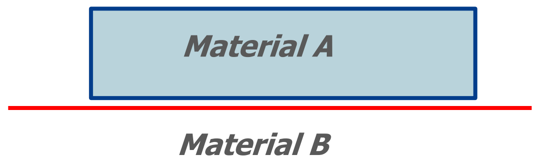
Relevant tests and models to measure the aptitude of powders to acquire ES charges

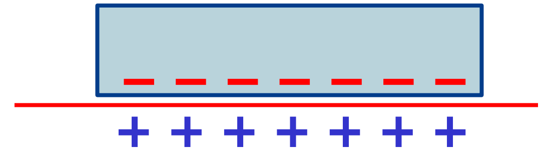


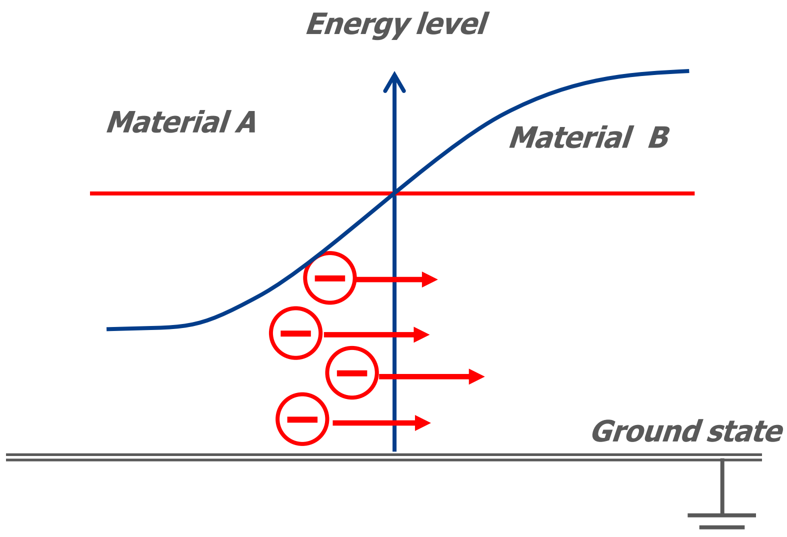


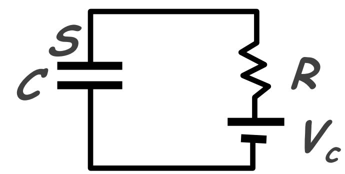


Contact charging (triboelectrification)









$$dq = C.S\left\{1 - \exp\left(dt / t\right)\right\}V_c$$

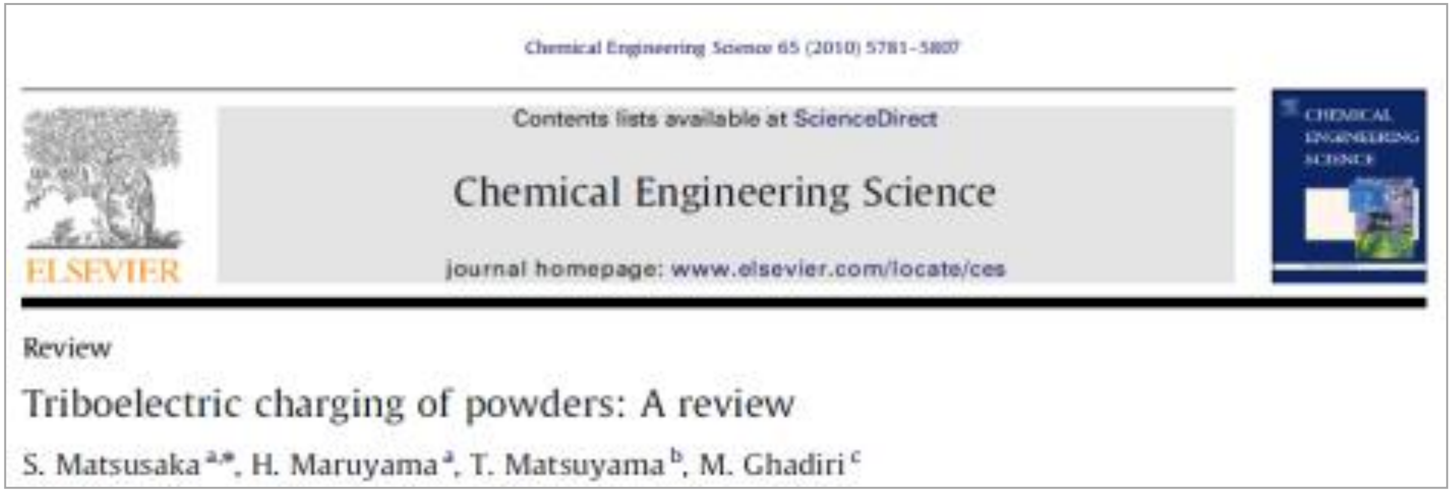
Three different cases :

Conductor-Conductor

Conductor-Insulator

Insulator-Insulator

Electron potential energy for metal–metal contact.



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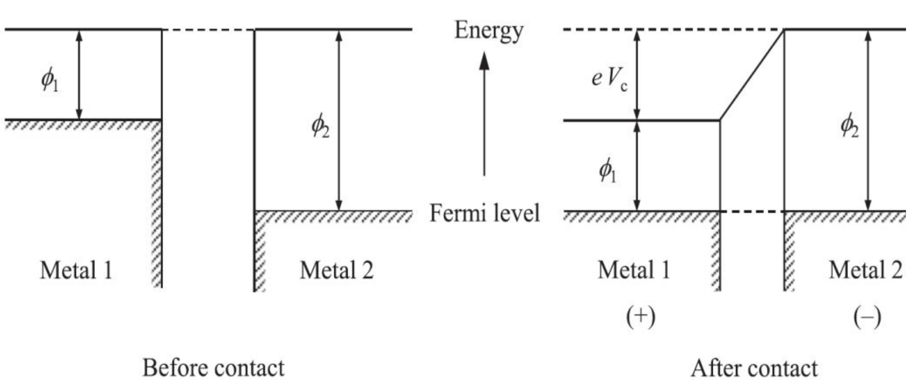
Review

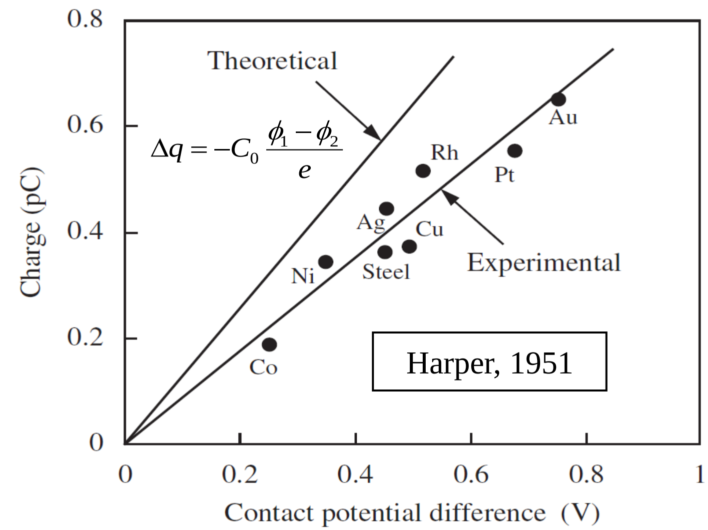
Triboelectric charging of powders: A review

S. Matsusaka [a,*], H. Maruyama [a], T. Matsuyama [b], M. Ghadiri [c]

Charge transfer tends to equalize the energy level

$$\Delta q = -C_0 \frac{\phi_1 - \phi_2}{e}$$





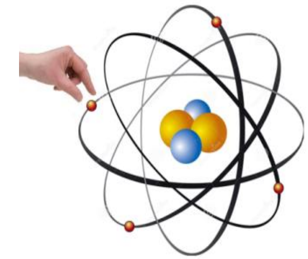
Main reasons for error: Surface roughness, impurities, oxidized layer, separation speed.

Electron potential energy for metal–metal contact.

Electron Transfer based on the Contact Potential Difference (CPD)

work function : the minimum amount of energy needed to remove an electron from the metal

Fermi Level : the energy of the electrons of the outer layer of atoms



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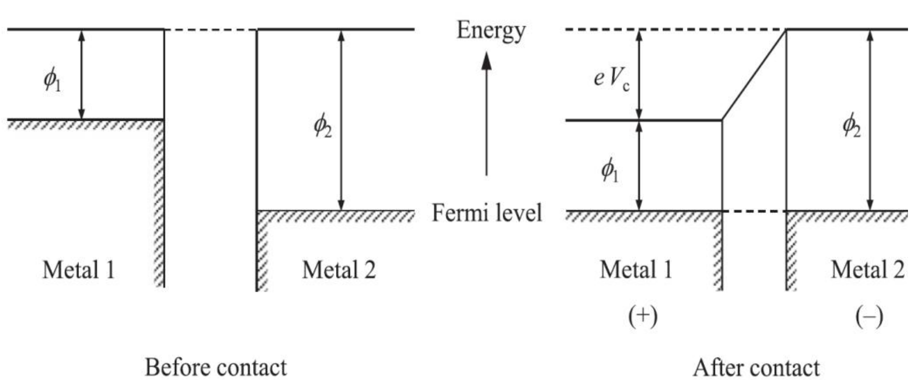
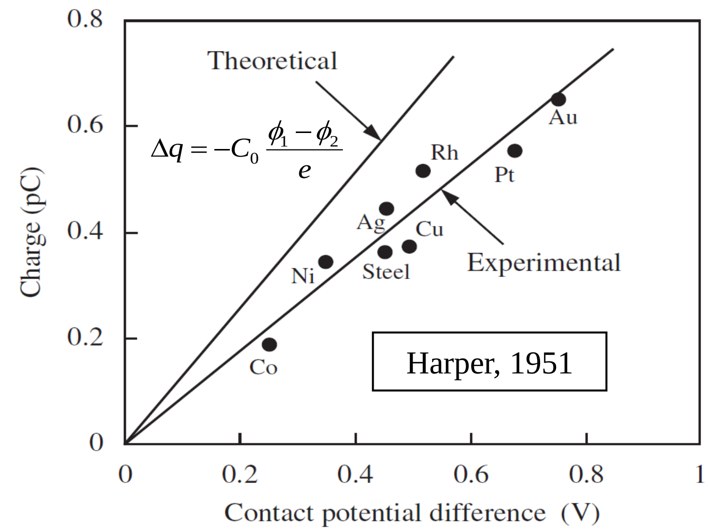
$$\Delta q = -C_0 \frac{\phi_1 - \phi_2}{e}$$

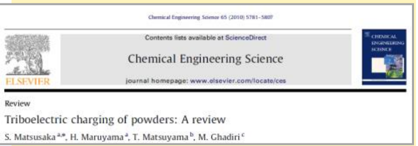




Main reasons for error: Surface roughness, impurities, oxidized layer, separation speed.

Insulator–metal & Insulator–Insulator contacts

~~Classical Physics~~ ⇨ Quantum Physics (Tunnel effect)



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Review

Triboelectric charging of powders: A review

S. Matsusaka, H. Maruyama, T. Matsuyama, M. Ghadiri

Analogous concept of "effective work function"

$$\Delta q = -C_0 \frac{\phi_I - \phi_M}{e}$$

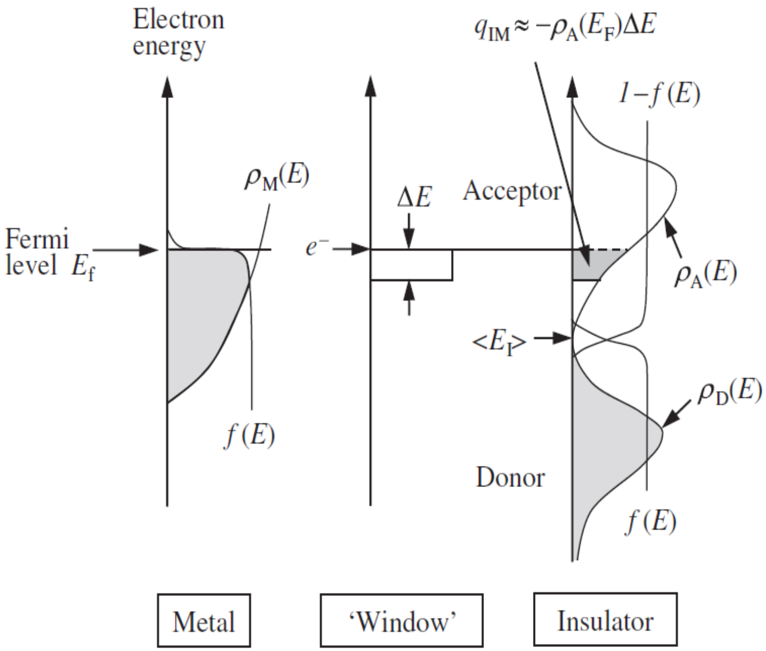


Fig. 5. Molecular-ion-state model for a metal–insulator contact (electron injection into acceptor states of polymer).

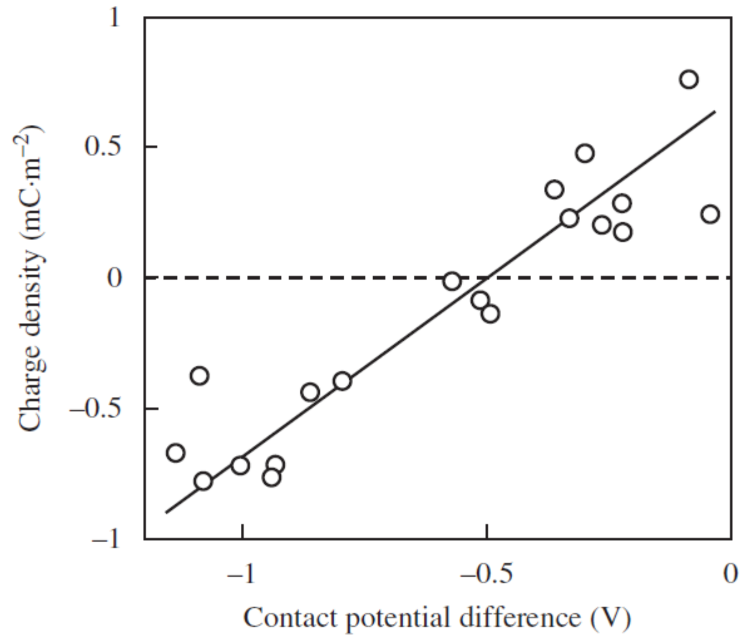
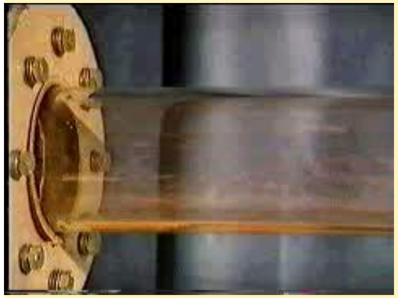
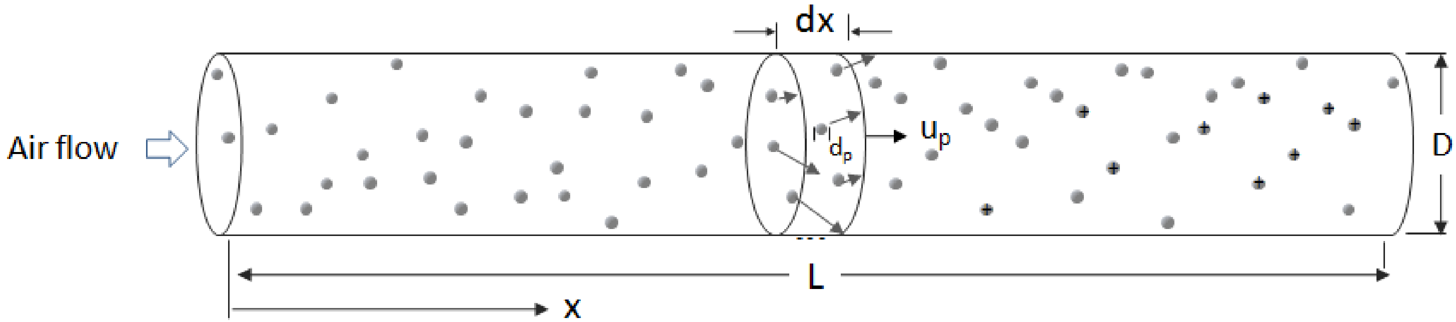


Fig. 3. Charge density of Nylon 66 by contact with various metals. The horizontal axis is the CPD of gold against each metal $V_{Au/M}$ (Davies, 1969).

☞ The effective work function can't be measured directly but must be established at specified conditions by application tests

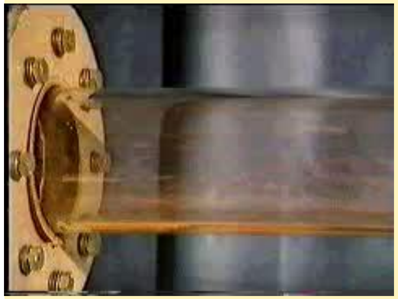
Modelling of charge transfer in dilute phase transport



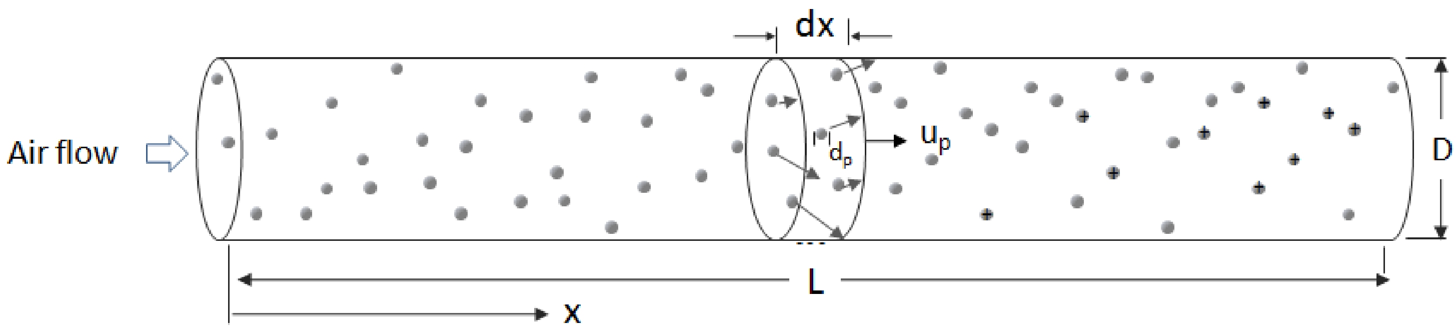


Model’s Hypothesis:

- *dilute phase transport ⇨ particle-wall collisions are dominant*
- *the flow of both particles and the carrier gas is uniform*
- *all particles have the same probability to collide with the wall*
- *charge distribution and bi-polar charging are neglected*
- *the charge is evenly distributed all over the solids surfaces*
- *the system is considered to be lowly to moderately charging (charge-to-surface ratios less than $10^{-2}C.m^{-2}$)*



Modelling of charge transfer in dilute phase transport



Charge conservation law:

ψ : charge density inside the control volume

σ : current density (i.e. electric current per unit area)

$$\frac{\partial \psi(x,t)}{\partial t} + \nabla \times \sigma(x,t) = R(x,t)$$

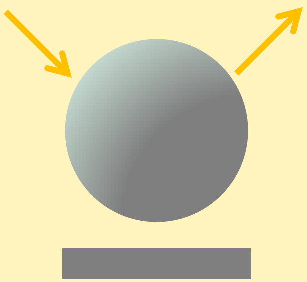
charge accumulation inside the elemental volume

charge variation due to flow of charged particles

rate of charge transfer between the particles and the wall

Charge conservation law

Particles



Wall

$$\psi_p(x,t) = \frac{6\beta}{d_p}\varsigma_p(x,t)$$

$$\sigma = \frac{24\dot{m}}{\pi\rho_p d_p D^2}\varsigma_p(x,t)$$

$$\frac{\partial\psi(x,t)}{\partial t} + \nabla \times \sigma(x,t) = R(x,t)$$

$$R(x,t) = \frac{6f\beta}{\pi d_p^3}v(x,t)$$

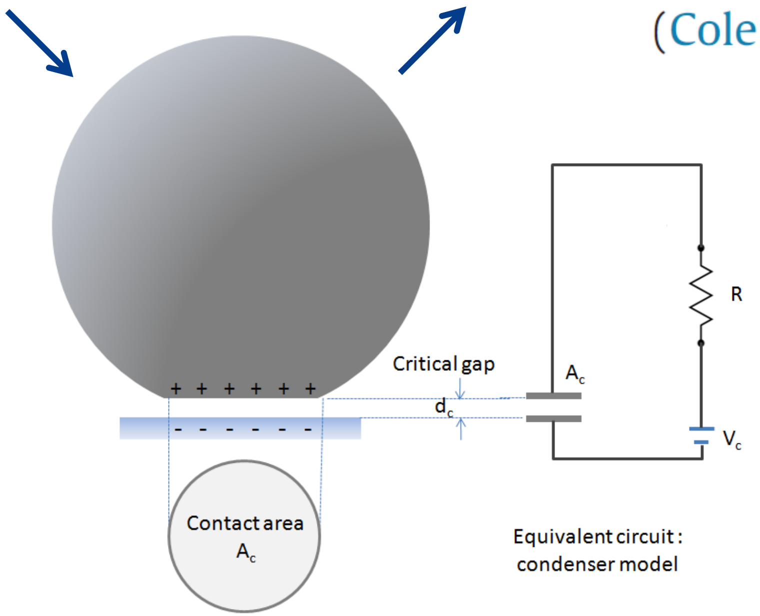
$$\psi_w(x,t) = \frac{4}{D}\varsigma_w(x,t)$$

$$\sigma = 0$$

$$v(x,t) = f(\varsigma_p, \varsigma_w)$$

	Local charge density	Total charge
Particles	$\frac{\partial\varsigma_p(x,t)}{\partial t} + u_p\frac{\partial\varsigma_p(x,t)}{\partial x} = \frac{f}{\pi d_p^2}v(x,t)$	$Q_p(t) = \frac{6\dot{m}}{\rho_p d_p}\int_0^t \varsigma_p(L,t)dt$
Wall	$\frac{\partial\varsigma_w(x,t)}{\partial t} = \frac{3f\beta D}{2\pi d_p^3}v(x,t)$	$Q_w(t) = \pi DL\int_0^L \varsigma_w(x,t)dx$

Rate of charge transfer *R(x,t)* ?



(Cole et al., 1969-70; Masuda et al., 1976).

$$v(x,t) = \alpha V_s$$

$$V_s = V_c - \frac{A_c}{4\pi\varepsilon d_c}(\varsigma_p + \varsigma_w)$$

$$\downarrow$$

$$V_c = \varphi_p - \varphi_w$$

Simple-condenser model

$$R(x,t) = \frac{6f\beta}{\pi d_p^3} v(x,t)$$

$$v(x,t) = \alpha\left(V_c - \frac{A_c}{4\pi\varepsilon d_c}(\varsigma_p + \varsigma_w)\right)$$

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Normalized model equations

	Dimensionless local charge density	Dimensionless total charge
Particles	$\dfrac{\partial Y}{\partial t^*} + \dfrac{\partial Y}{\partial x^*} = K_p\left(1 - Y - Z\right)$	$Q_p^*\left(t^*\right) = \int_0^{t^*} Y\left(1, t^*\right) dt^*$
Wall	$\dfrac{\partial Z}{\partial t^*} = K_w\left(1 - Y - Z\right)$	$Q_w^*\left(t^*\right) = \int_0^{1} Z\left(x^*, t^*\right) dx^*$

Dimensionless variables

$x^* = \dfrac{x}{L}$	$t^* = \dfrac{u_p t}{L}$	$K_p = \dfrac{\beta f}{16\pi} \dfrac{\rho_p}{\dot{m}} \dfrac{LD^2}{d_p^2} \dfrac{A_c \alpha}{\varepsilon d_c}$
$Y = \dfrac{A_c \varsigma_p}{4\pi\varepsilon d_c V_c}$	$Z = \dfrac{A_c \varsigma_w}{4\pi\varepsilon d_c V_c}$	$K_w = \dfrac{3 f \beta^2}{32\pi} \dfrac{\rho_p}{\dot{m}} \dfrac{LD^3}{d_p^3} \dfrac{A_c \alpha}{\varepsilon d_c}$
$Q_p^*\left(t^*\right) = \dfrac{A_c d_p}{6\pi^2 \varepsilon d_c V_c \beta D^2 L} Q_p(t)$	$Q_w^*\left(t^*\right) = \dfrac{A_c}{4\pi^2 L^2 D \varepsilon d_c V_c} Q_w(t)$	

Normalized model equations

	Dimensionless local charge density	Dimensionless total charge
Particles	$\frac{\partial Y}{\partial t^*} + \frac{\partial Y}{\partial x^*} = K_p(1 - Y - Z)$	$Q_p^*(t^*) = \int_0^{t^*} Y(1, t^*) dt^*$
Wall	$\frac{\partial Z}{\partial t^*} = K_w(1 - Y - Z)$	$Q_w^*(t^*) = \int_0^1 Z(x^*, t^*) dx^*$

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Modelling of spatio-temporal evolution of electrostatic charge transfer during the pneumatic transport of powders: General solutions and special cases

Khashayar Saleh *

Normalized model equations

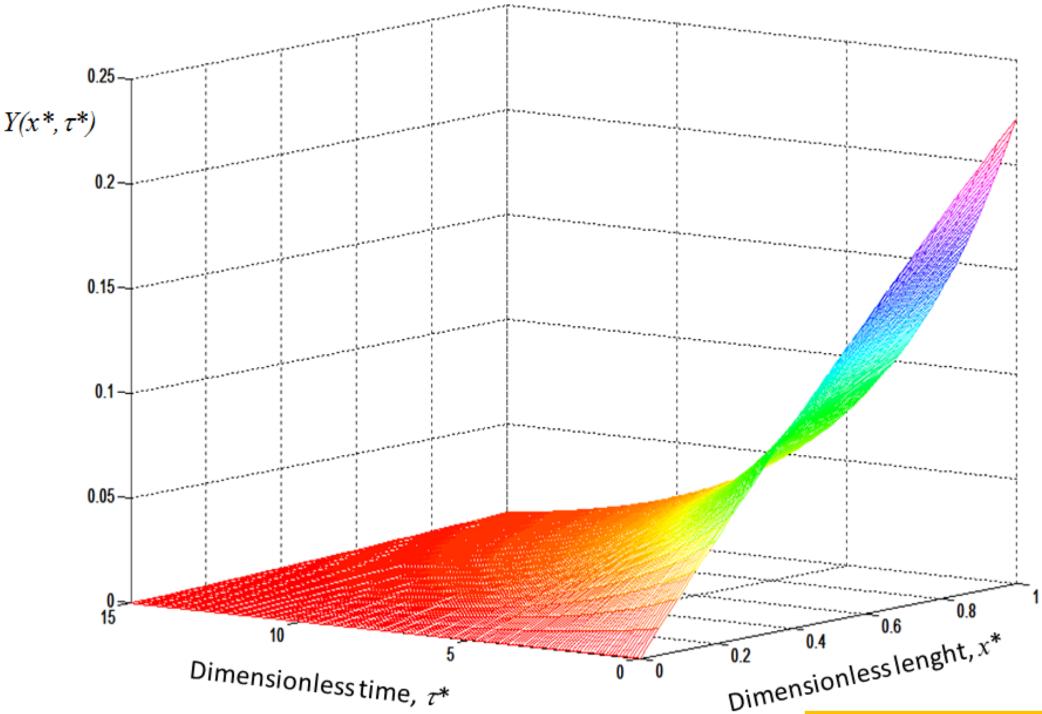
	Dimensionless local charge density	Dimensionless total charge
Particles	$\frac{\partial Y}{\partial t^*} + \frac{\partial Y}{\partial x^*} = K_p(1-Y-Z)$	$Q_p^*(t^*) = \int_0^{t^*} Y(1,t^*)dt^*$
Wall	$\frac{\partial Z}{\partial t^*} = K_w(1-Y-Z)$	$Q_w^*(t^*) = \int_0^1 Z(x^*,t^*)dx^*$

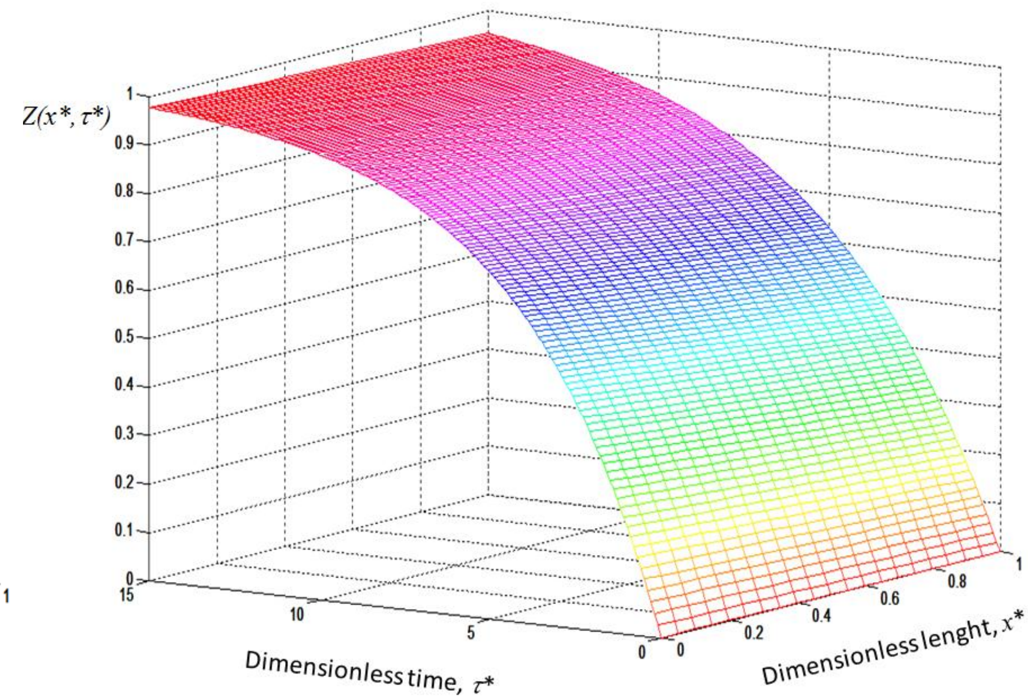
Analytical solution

$$Y(x^*,\tau^*) = Y_0 + K_p(1-Y_0-Z_0)\left(1-J\left(\frac{x^*}{K_p}, K_w\tau^*\right)\right)$$

$$Z(x^*,\tau^*) = (Y_0+Z_0-1)I_0\left(2\sqrt{K_pK_wx^*\tau^*}\right)exp\left(-K_px^*-K_w\tau^*\right)+1-Y(x^*,\tau^*)$$

Example of Modelling results





Model Parameters

$$K_p = K_w = 0.25$$

$$Y_0 = Z_0 = 0$$

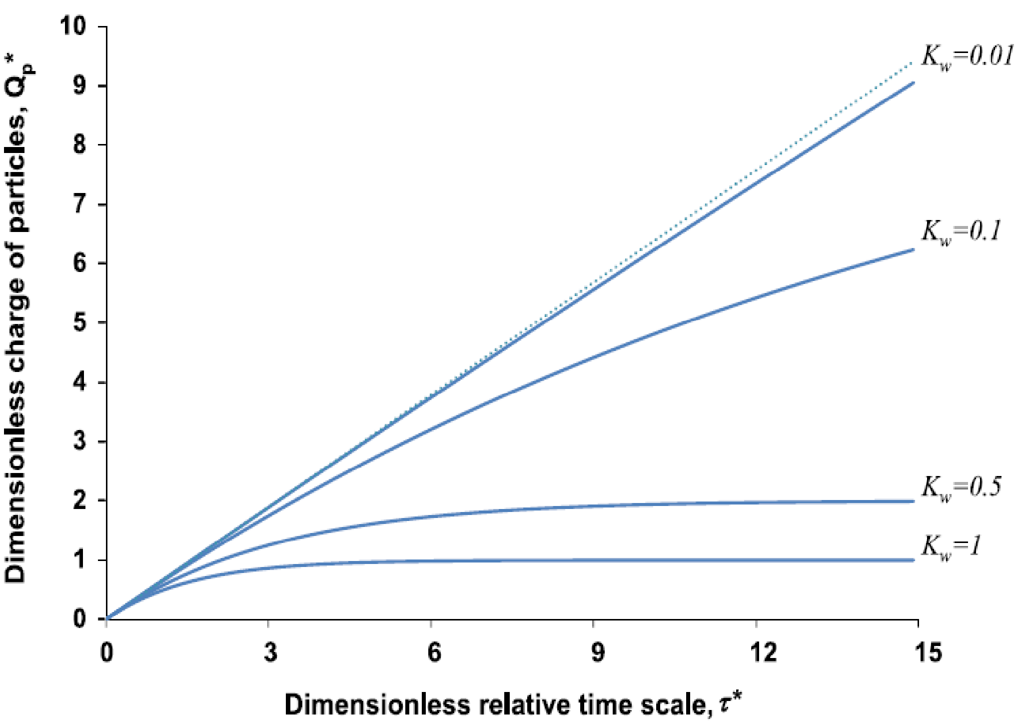
Analytical solution

$$Y\left(x^*,\tau^*\right) = Y_0 + K_p\left(1 - Y_0 - Z_0\right)\left(1 - J\left(\frac{x^*}{K_p}, K_w\tau^*\right)\right)$$

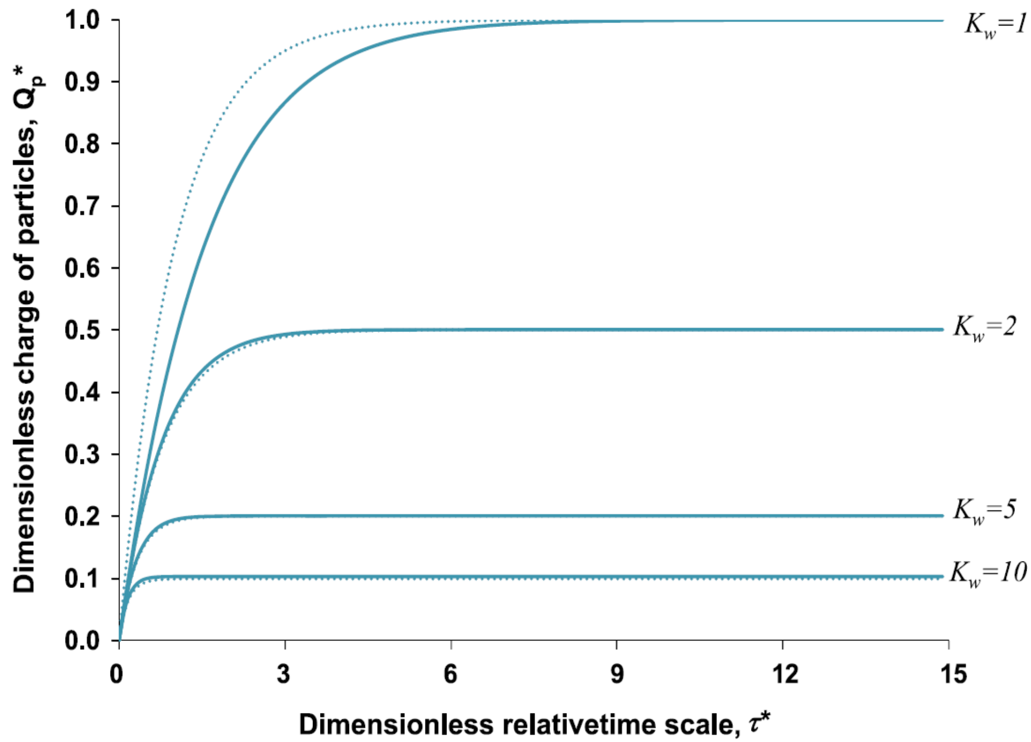
$$Z\left(x^*,\tau^*\right) = \left(Y_0 + Z_0 - 1\right)I_0\left(2\sqrt{K_pK_wx^*\tau^*}\right)exp\left(-K_px^* - K_w\tau^*\right) + 1 - Y\left(x^*,\tau^*\right)$$

Modelling results

Effect of the charge transfer constants, K_p & K_w



$K_w < K_p$



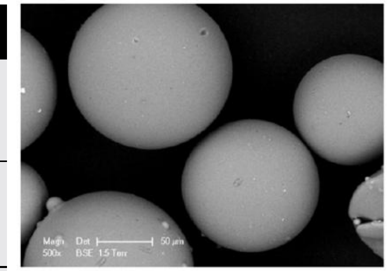
$K_w > K_p$

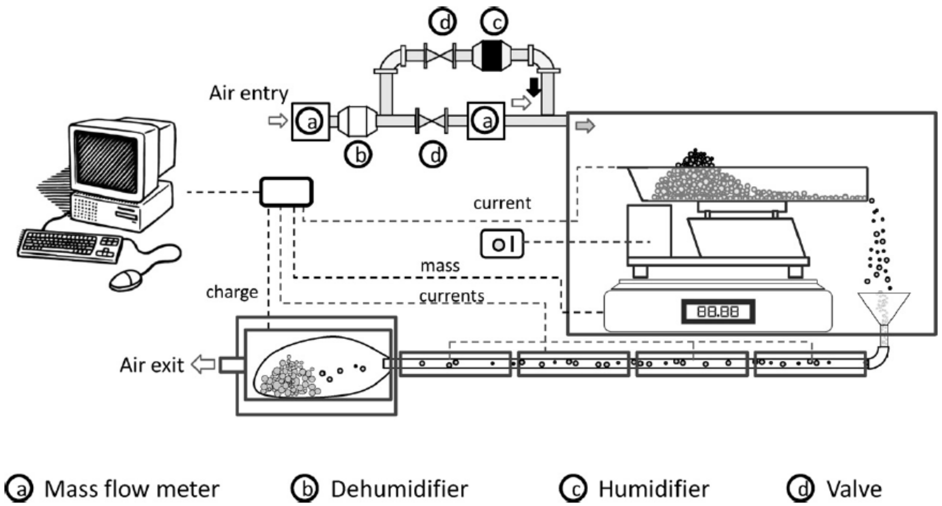
Example of time evolution of the dimensionless accumulated charge of particles (K_p=1, Y_0=Z_0=0)

Experimental validation of the model

Parametric study

Table 2 – some characteristics of material used.			
Particles	Size interval (μm)	Shape factor[a]	Density $kg\,m^{-3}$
Glass beads	75–150, 150–250, 250–500	≈1	2495
Crushed glass	150–250, 250–500	0.69	2495





Objective :

- To identify the relevant parameters involved in tribocharging of powders during dilute phase PT and to study their effects

Experimental validation of the model
Parametric study

Table 2 – some characteristics of material used.

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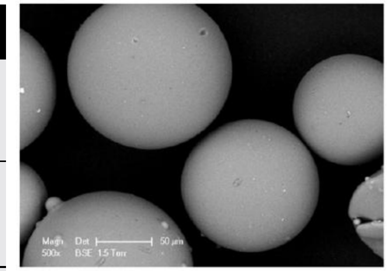

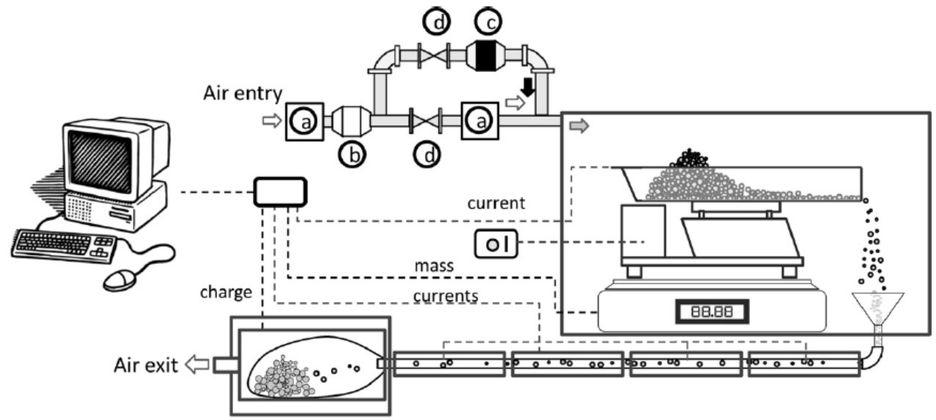

ⓐ Mass flow meter ⓑ Dehumidifier ⓒ Humidifier ⓓ Valve

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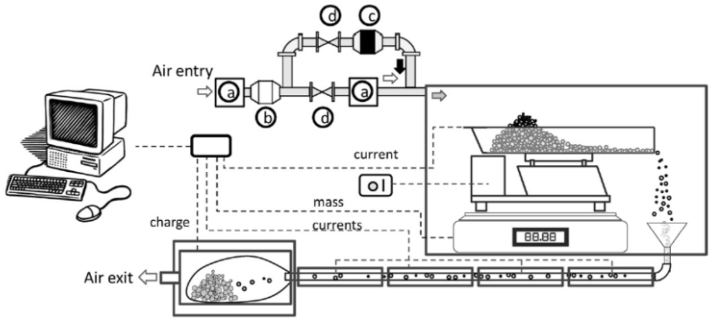
Relevant parameters involved in tribocharging of powders during dilute phase pneumatic transport

Khashayar Saleh, Adoum Traore Ndama, Pierre Guigon*

Experimental validation of the model

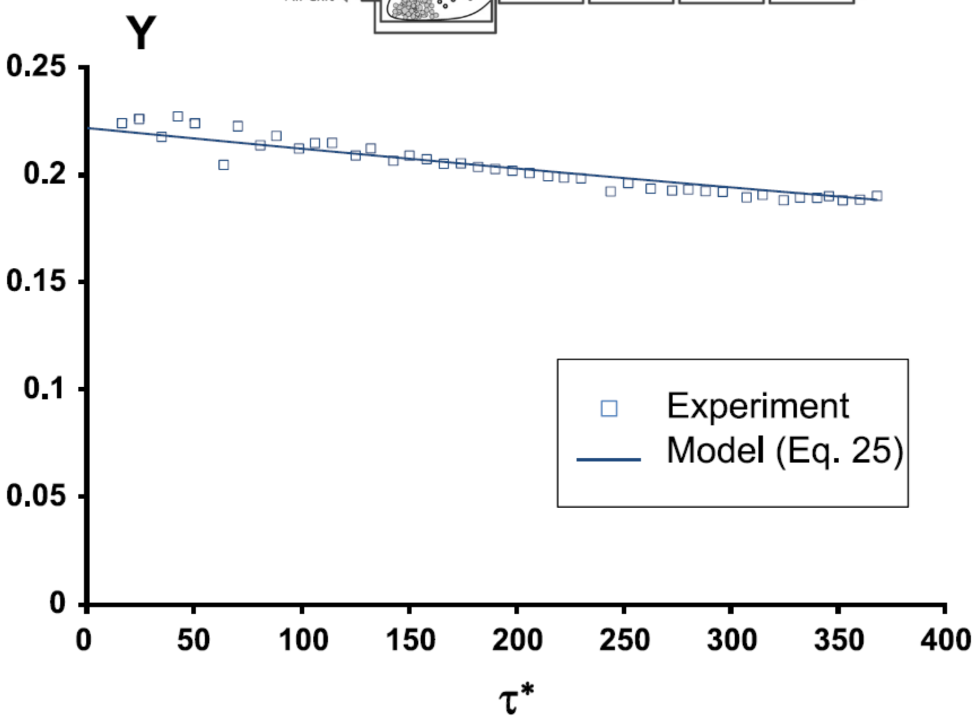


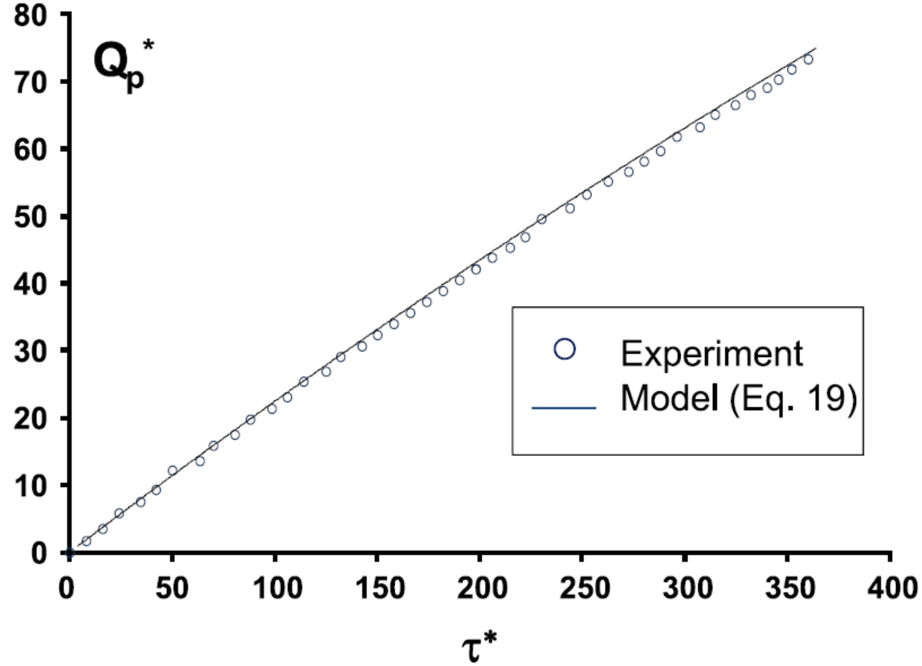
vs.

Analytical solution

$$Y\left(x^*,\tau^*\right)=Y_0+K_p\left(1-Y_0-Z_0\right)\left(1-J\left(\frac{x^*}{K_p},K_w\tau^*\right)\right)$$

$$Z\left(x^*,\tau^*\right)=\left(Y_0+Z_0-1\right)I_0\left(2\sqrt{K_pK_wx^*\tau^*}\right)exp\left(-K_px^*-K_w\tau^*\right)+1-Y\left(x^*,\tau^*\right)$$





Operating conditions.

Air flow rate (kg s^{-1})	7.85×10^{-5}
Particles flow rate (kg s^{-1})	2.00×10^{-3}
volume-based solids loading (-)	1.02×10^{-2}
Relative humidity (%)	5
Temperature (°C)	20

Material properties.

Work function of glass beads, ϕ_p (J)	8.0×10^{-19}
Work function of the wall (PTFE), ϕ_p (J)	9.20×10^{-19}
Air permittivity (F m^{-1})	8.85×10^{-12}
Particle density (kg m^{-3})	2495
Particle mean diameter (μm)	100

Identified parameters K_p=0.25, A_c/d_c=2×10^{-5} m) utc Université de Technologie Compiègne

Conclusions

- A macroscopic multi-scale model was developed using a mechanistic approach for charge transfer during single collisions

- The model provides a general frame to describe the simultaneous evolution of particles and wall charging

- Better understanding and rational explanation of phenomena

- Could be extended to other operations (*e.g.* fluidization)

- Establish reliable triboelectric series

- STEP-2 : toward a predictive model?