Electrostatics of Granular Flow in Pneumatic Systems

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STEP 1 (Static-Tribo-Electricity of Powder) 2014/12/19-12/21
Soka University, Hachioji, Tokyo, Japan

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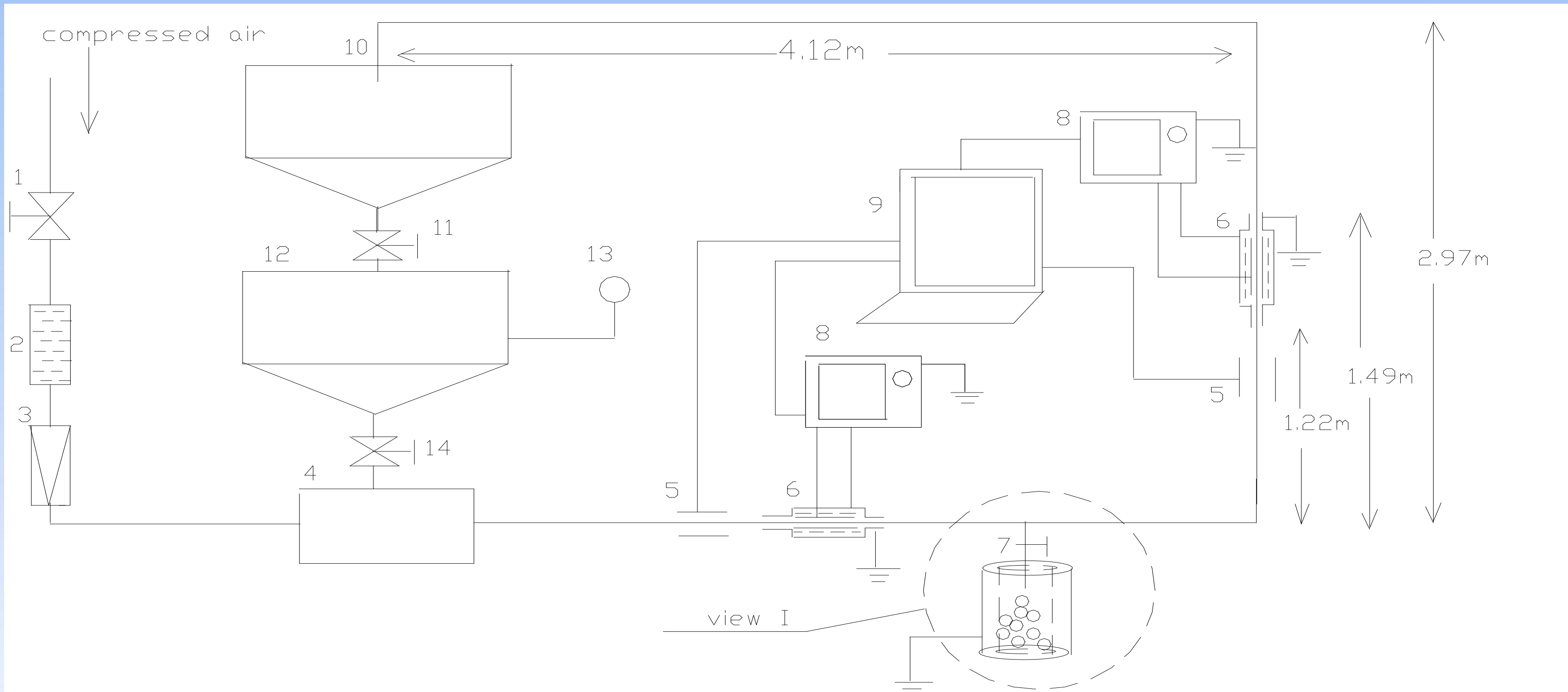
Background - 8.2 Kunshan Powder Explosion Accident

In a polishing workshop powder induced a extremely large accident (96 person die).

Possible reason: particle-particle/particle-wall interaction causes electrostatic charge and charges accumulate, which grows more and more to become explosion source.

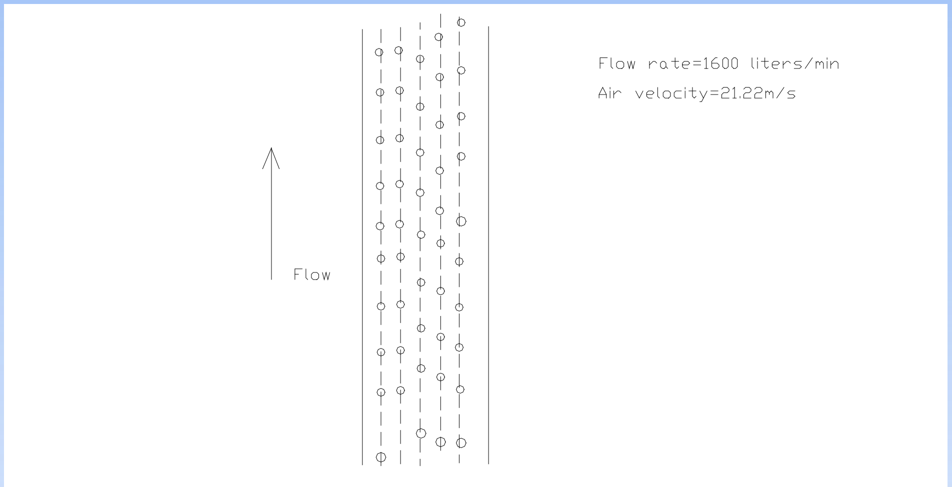
Experiment setup



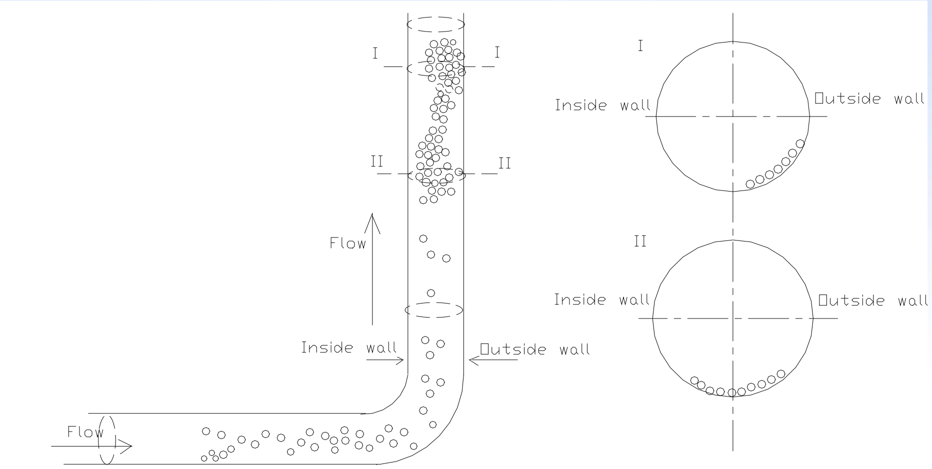
Particles conveying style	Cycle	Particle diameter:	2.8 mm
Particle material:	Polypropylene(PP)	Particle density:	1123 kg/m^3
Pipe material:	Polyvinyl Chloride (PVC)	Pipe diameter(inner):	40.0 mm
Pipe thickness:	5.0 mm	Relative humidity:	5%
Air flow rate:	860~1600 liters/min	Air superficial velocity:	11.4~21.2 m/s
Temperature:	28~30 ° C		

Yao et al. 2004. *Ind. Eng. Chem. Res.* 43, 7181-

Disperse flow -1600 L /min pattern observed in the vertical pipe



Initial condition

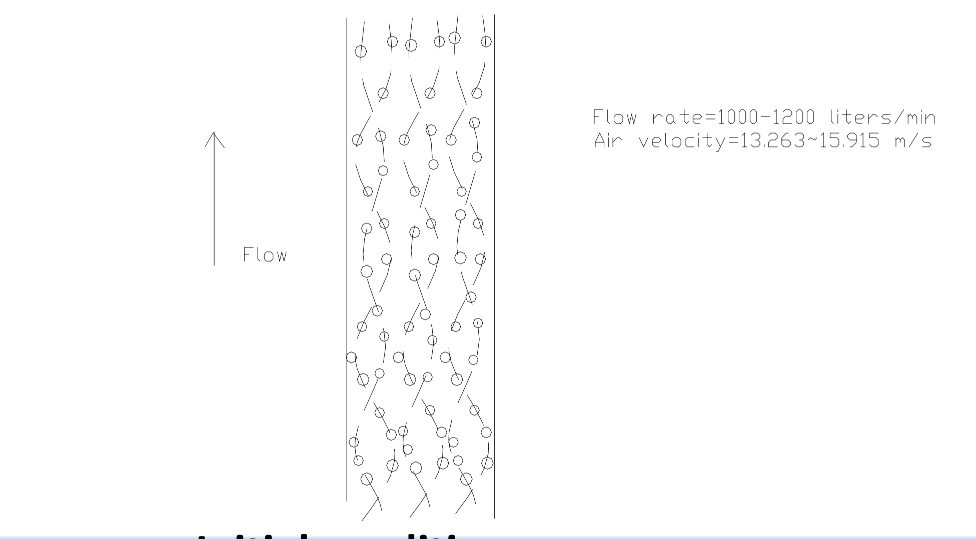


Two hours later

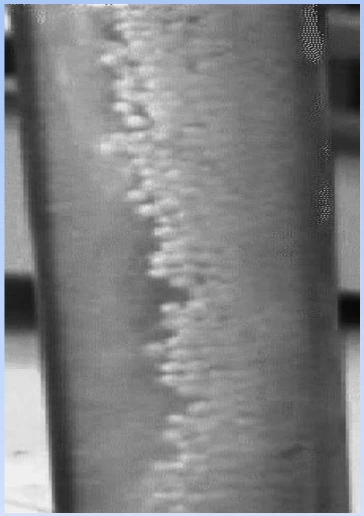
The clusters were located fairly high up in the pipe and traveled along a curved path by the pipe
wall. These clusters appeared and disappeared intermittently in an unpredictable manner.

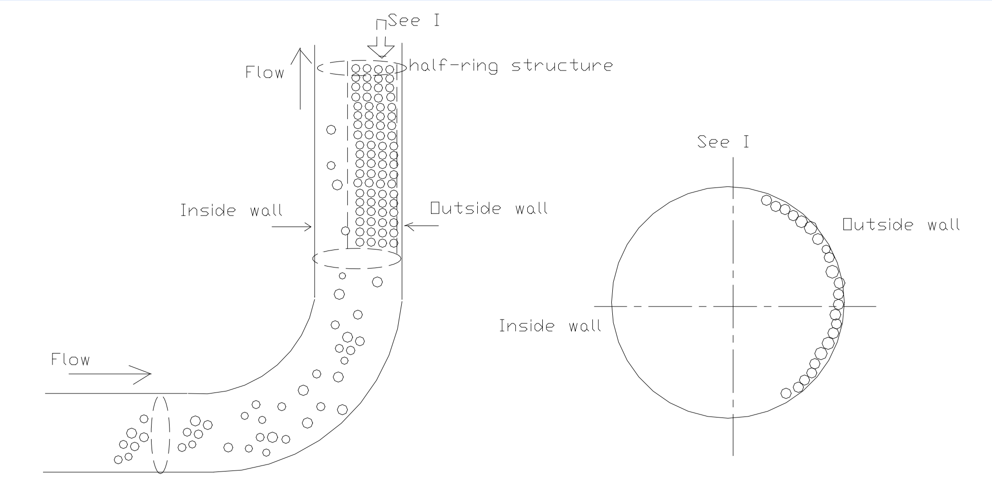
Yao et al. 2004. *Ind. Eng. Chem. Res.* 43, 7181-

Half-ring flow – 1100L/min
- vertical granular pattern



Initial condition

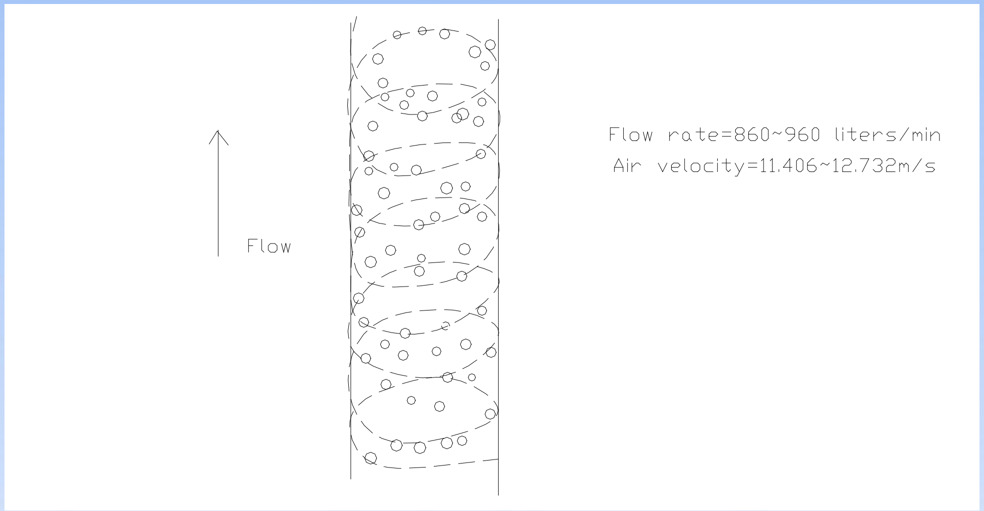




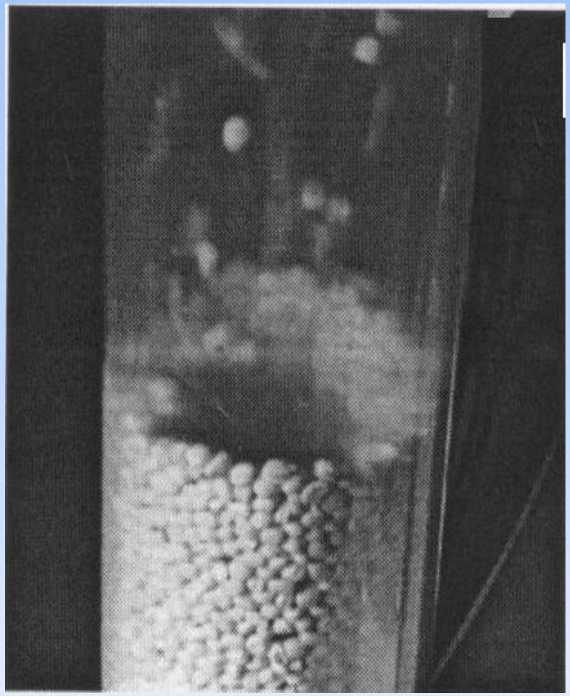
Half hour later

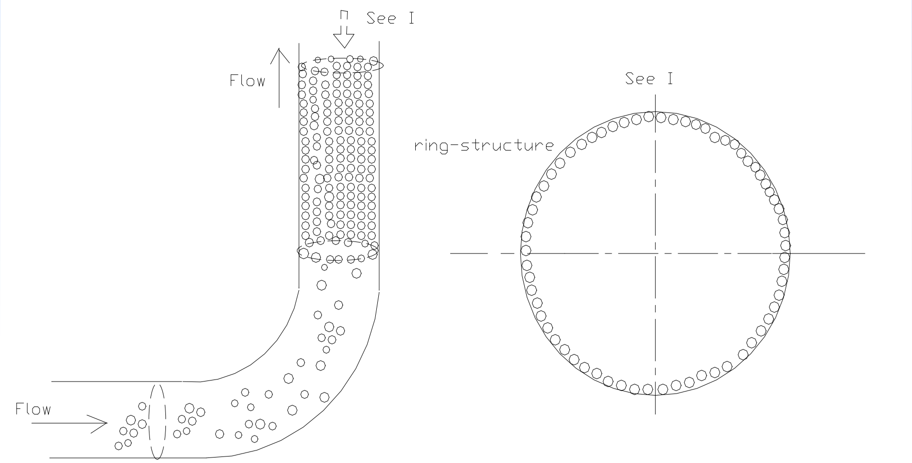
Particles were observed
to cluster on the side of the vertical pipe wall distant from the position of the lower horizontal pipe to form a half-annular ring structure

Ring flow – 960 L/min vertical granular pattern



Initial condition

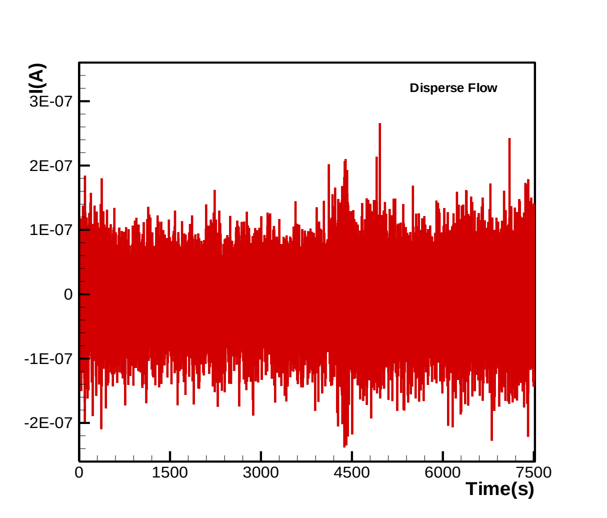




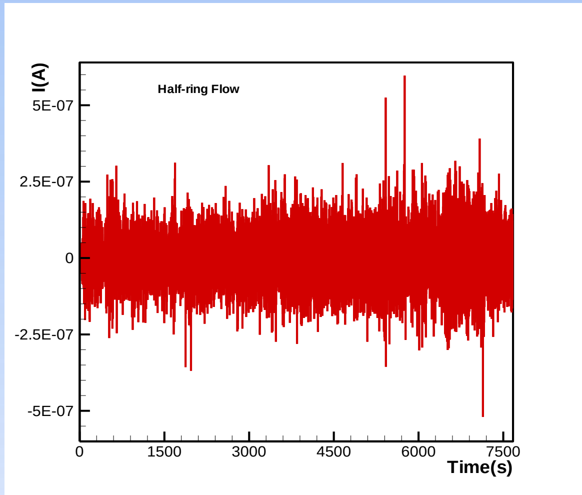
Fifteen minutes later

Particles were observed to
travel in a spiral fashion up the vertical
pipe along the
pipe wall. This resulted in a ring or annulus
structure with high particle concentrations
adjacent to the wall and a relatively empty
core region

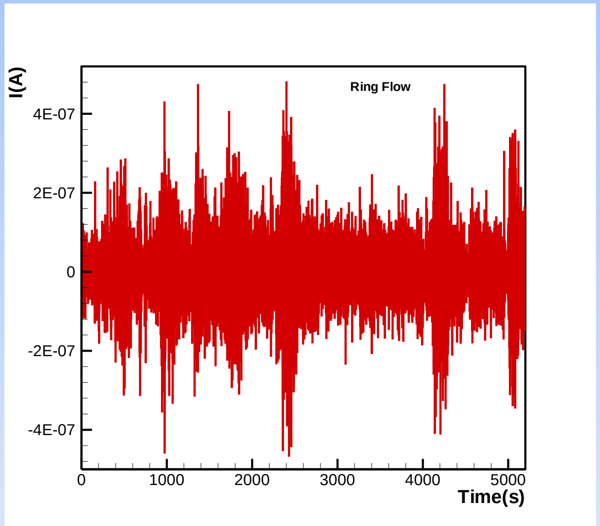
Induced current - vertical pipe



Disperse flow



Half-ring flow



Ring flow

Induced current acquired at the vertical pipe:

(left) disperse flow (air flow rate 1600 L/min, solids feed rate 35.3 (3.2 kg/m^2 s);
(middle) half-ring flow (air flow rate 1000 L/min, solids feed rate 13.8 (2.4 kg/m^2 s);
(right) ring flow (air flow rate 80 L/min, solids feed rate 8.1(1.6 kg/m^2 s).

Yao et al. 2004. *Ind. Eng. Chem. Res.* 43, 7181-

Induced current – vertical pipe

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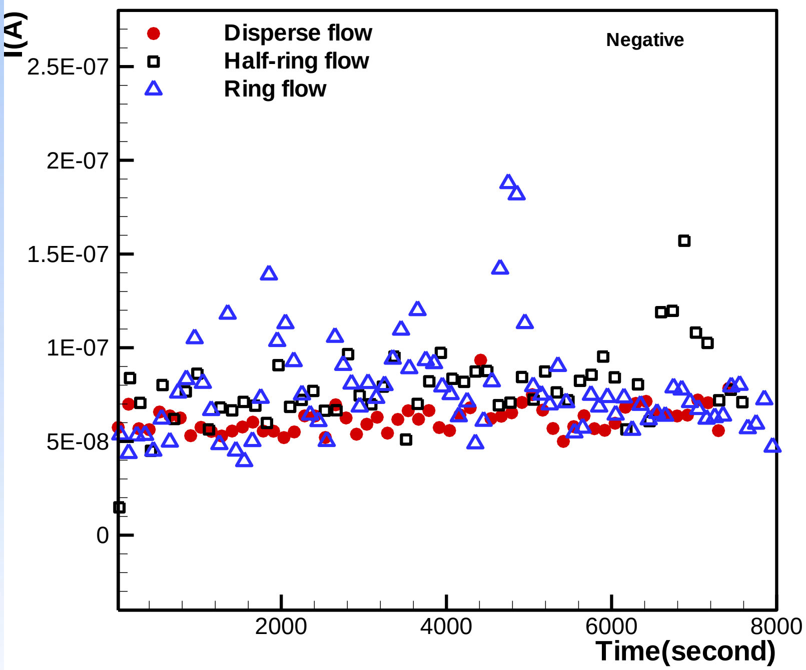
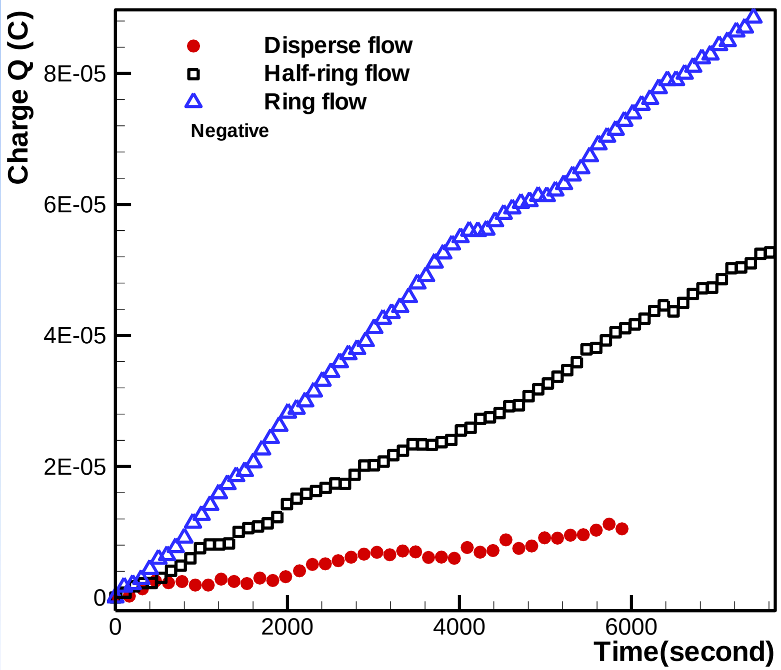




Left: Comparison of the current value (negative) for the three flows.

Right: Comparison of the charge accumulation for the three flows.

Electrostatic field simulation

- point-point charge sources

$$e = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_x^{\,2}}$$ (Halliday et al. 1997)

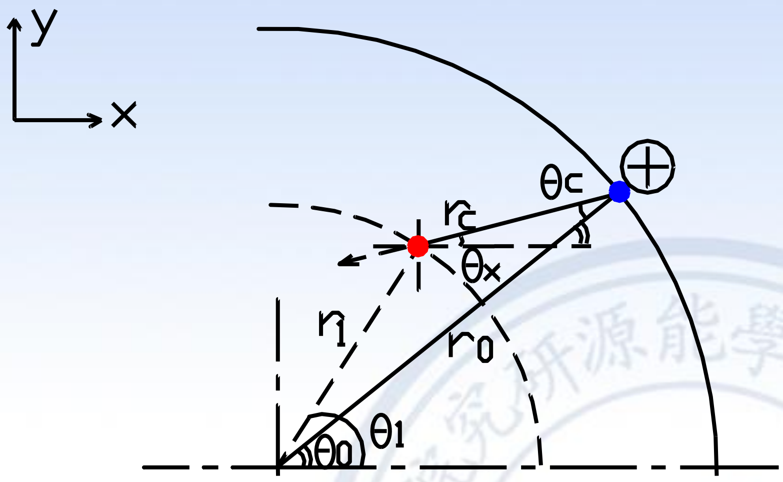
ε_0: permittivity constant (in vacuum $8.85 \times 10^{-12}\ C^2/N{\cdot}m^2$)
r_x : the distance from the point charge
q: the point charge

$$\frac{r_x}{\sin|\theta_0 - \theta_1|} = \frac{r_1}{\sin\theta_{xx}}$$

$$e_x = e \cdot \cos\theta_x = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_x^{\,2}} \cdot \cos\theta_x$$

$$e_y = e \cdot \sin\theta_x = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_x^{\,2}} \cdot \sin\theta_x$$

$$r_x^{\,2} = r_1^{\,2} + r_0^{\,2} - 2 \cdot r_1 \cdot r_0 \cdot \cos(\theta_0 - \theta_1)$$

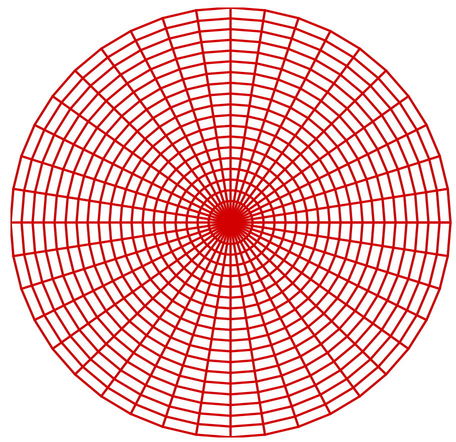


Halliday, D., et al. 1997.
***Fundamentals of Physics Extended. 5th ed.,* P558.**

Electrostatic field simulation
- point-points charge sources

In a two-dimension field, the electrostatic field generated by a point charge *q* at the point (*i, j*) can be calculated:

$$e_{x(i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2{}_{x(i,j)}} \cdot \cos\theta_{x(i,j)} \qquad e_{y(i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2{}_{x(i,j)}} \cdot \sin\theta_{x(i,j)}$$



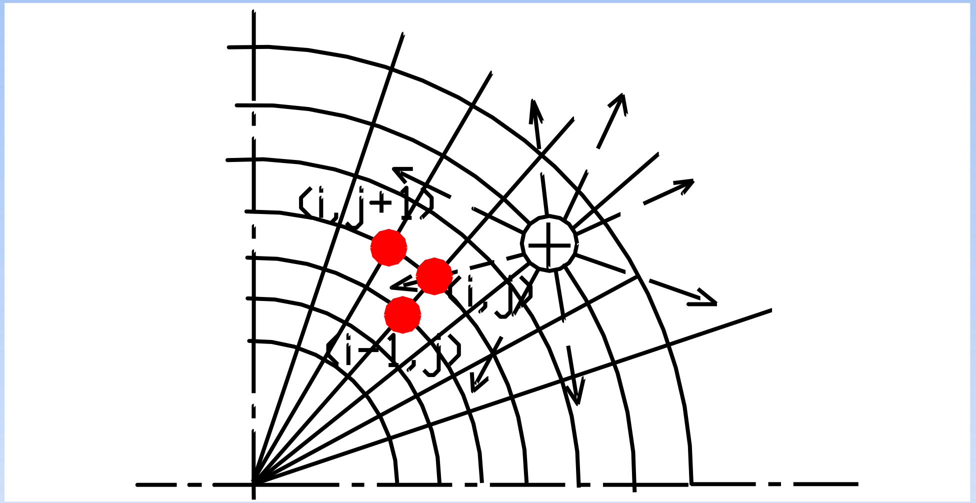
simulation grid (20×40)

Electrostatic field simulation

- points-points charge sources

$$e_{x(l,k,i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_{x(l,k,i,j)}} \cdot \cos\theta_{x(l,k,i,j)}$$

$$e_{y(l,k,i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_{x(l,k,i,j)}} \cdot \sin\theta_{x(l,k,i,j)}$$



$$E_{x(i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\sum_{i=1}^{m}\sum_{j=1}^{n} e_{x(l,k,i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\sum_{i=1}^{m}\sum_{j=1}^{n} \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_{x(l,k,i,j)}} \cdot \cos\theta_{x(l,k,i,j)}$$

$$E_{y(i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\sum_{i=1}^{m}\sum_{j=1}^{n} e_{y(l,k,i,j)} = \sum_{l=1}^{m}\sum_{k=1}^{n}\sum_{i=1}^{m}\sum_{j=1}^{n} \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_{x(l,k,i,j)}} \cdot \sin\theta_{x(l,k,i,j)}$$

$$E_{(i,j)} = \sqrt{E^2_{x(i,j)} + E^2_{y(i,j)}}$$

Electrostatic field

– pipe wall

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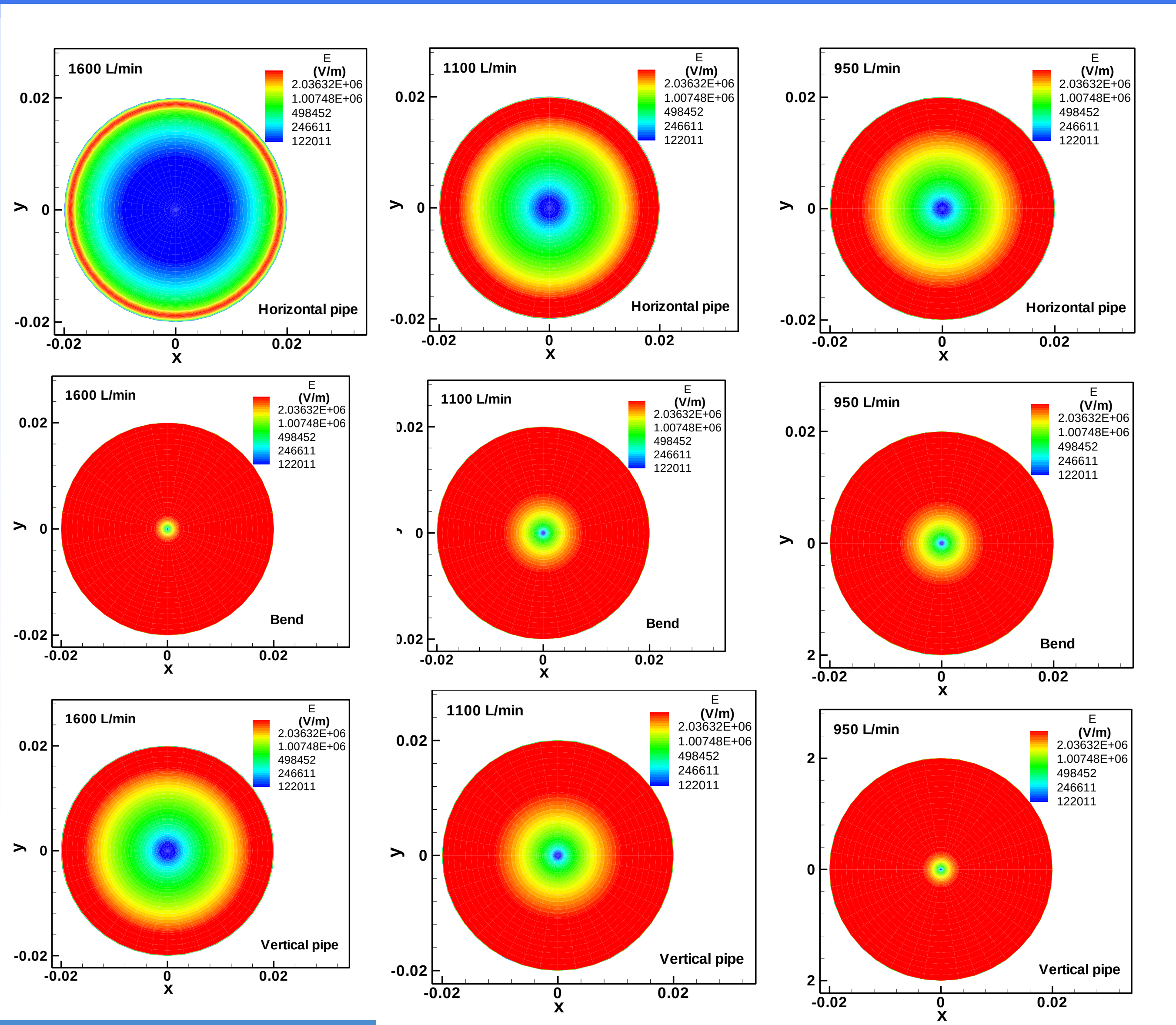


Horizontal

Bend

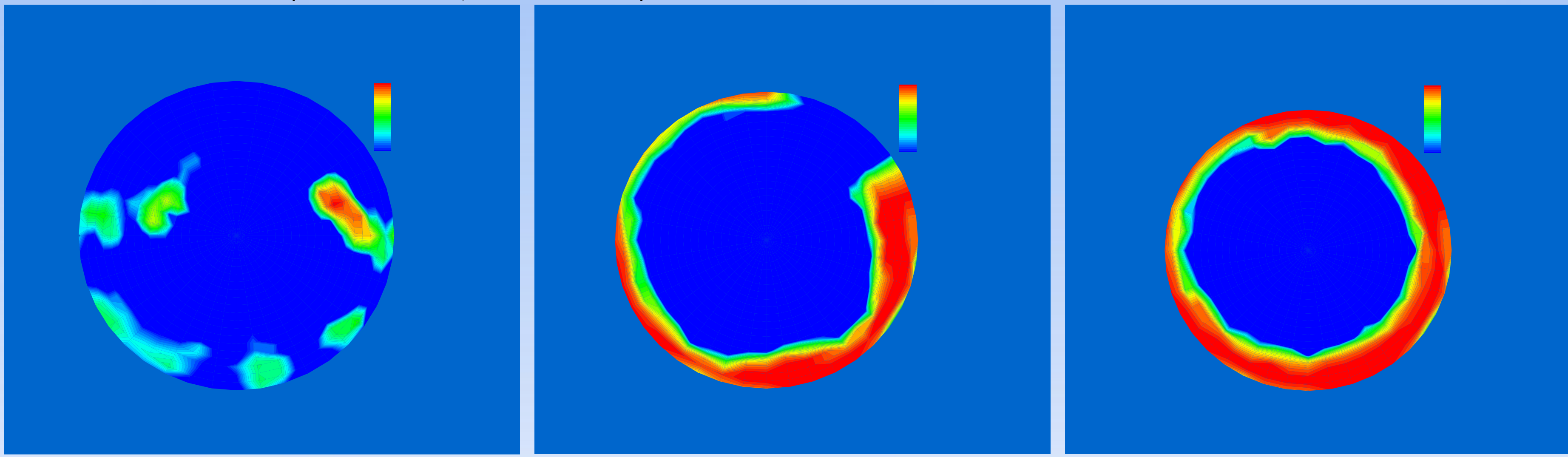
Vertical

Electrostatic field strength calculated for charged pipe wall (E: 1.22e5-1.22e7 V/m, 30 step)

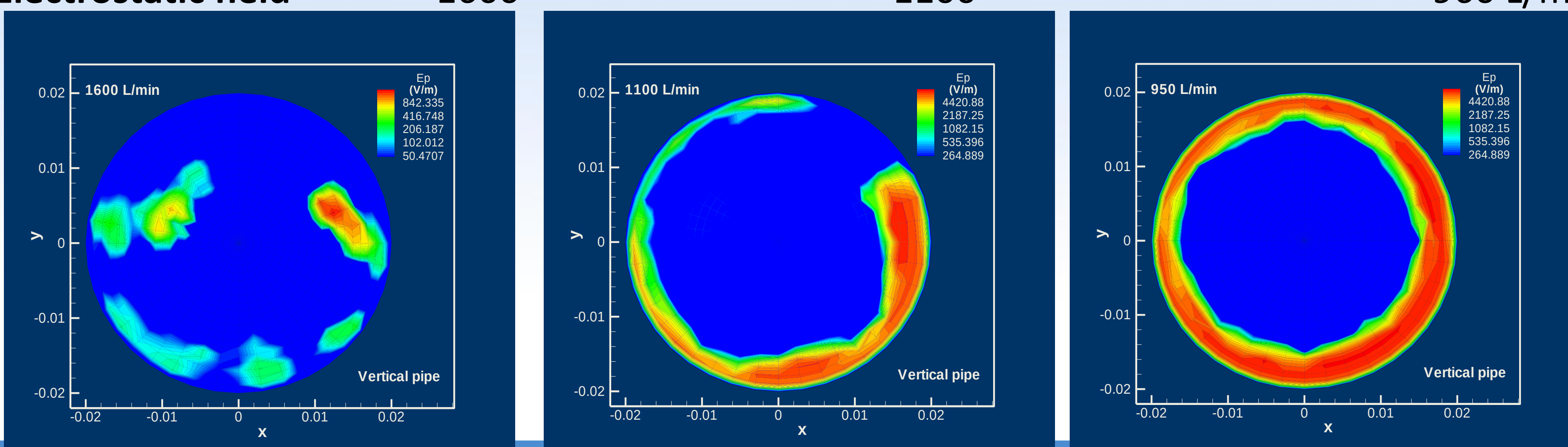
Yao et al. 2006 *AIChE J*. 52, 3775-.

ECT & Electrostatic field
- particles at vertical pipe

ECT solid fraction (Rao et al. 2001; Zhu et al. 2003)

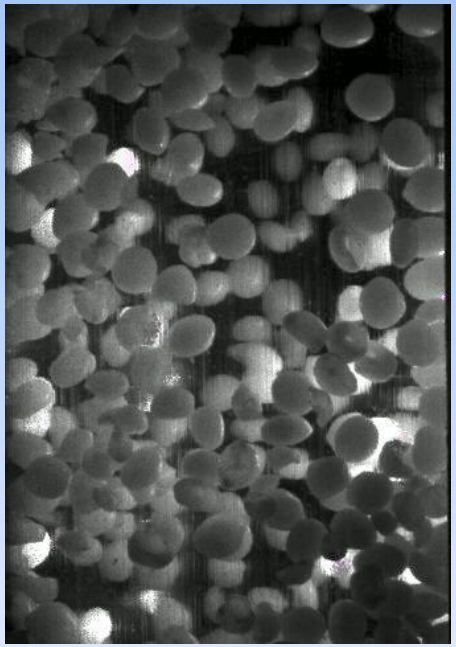
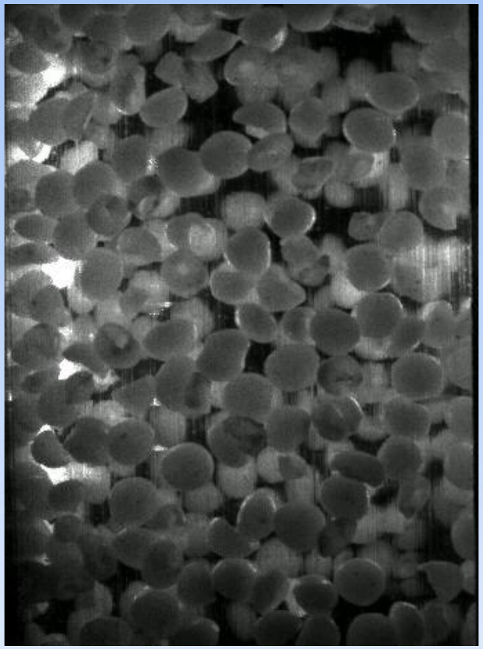


Electrostatic field 1600 1100 960 L/min



Yao et al. 2006 *AIChE J*. 52, 3775-.

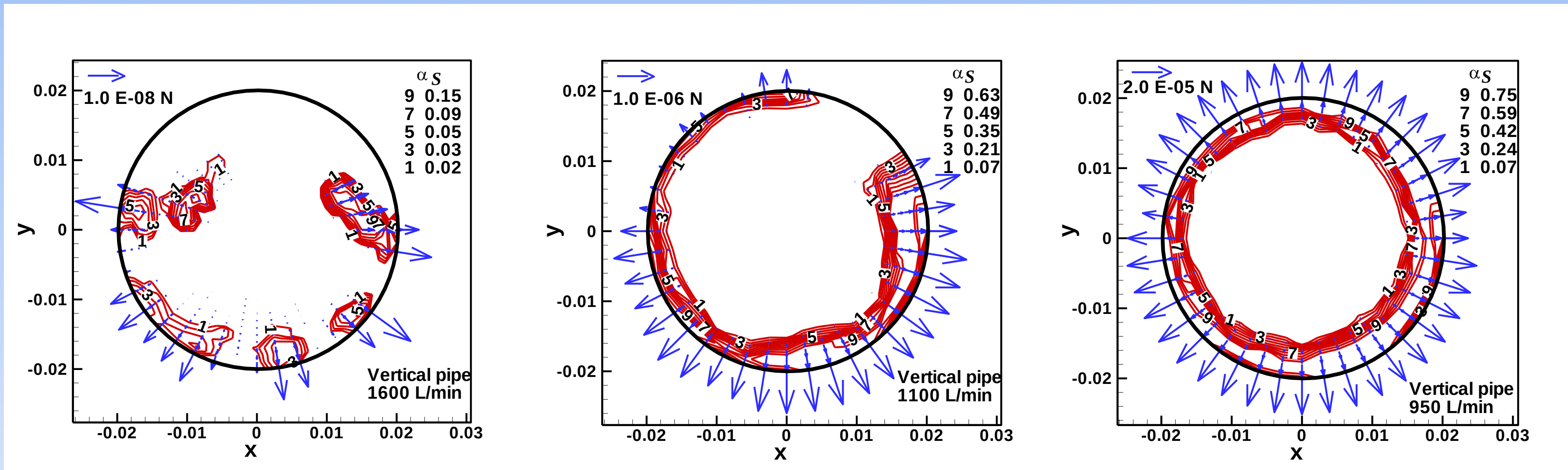
PIV measurements
– particles at vertical pipe

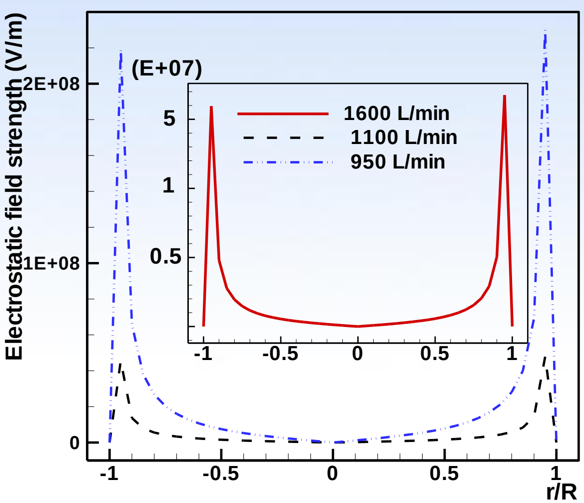




Air flow rate (L/min)	1600 (left)	1100(middle)	950(right)
(m/s):			
Core region (r/R<0.7):	5.10	-	-
Boundary region (0.8<r/R<1.0):	3.60	0.23	0.04
F_D (N):			
Boundary region (0.8<r/R<1.0):	1.62E-02	9.89E-04	1.65E-04

Yao et al. 2006 *AIChE J*. 52, 3775-.

Electrostatic force - particles at vertical pipe





The highest electrostatic force appears near the pipe wall and degrades from the pipe wall to the pipe center.

Electrostatic force increases with decreasing air flow rate.

Yao et al. 2006 *AIChE J*. 52, 3775-.

Dynamics analysis - particles at vertical pipe

	Air flow rate (L/min)	Gravity (N)	F_D (N)	F_f (N)	F_E (N)
Core region:	1600	1.27E-04	7.56E-02	2.62E-12~1.19E-09	4.68E-12~2.13E-09
Boundary region:	1600	1.27E-04	1.62E-02	1.00E-09~1.25E-08	1.79E-09~2.23E-08
	1100	1.27E-04	9.89E-04	5.26E-09~2.35E-06	9.39E-09~4.19E-06
	950	1.27E-04	1.65E-04	3.60E-07~1.89E-05	6.42E-07~3.37E-05

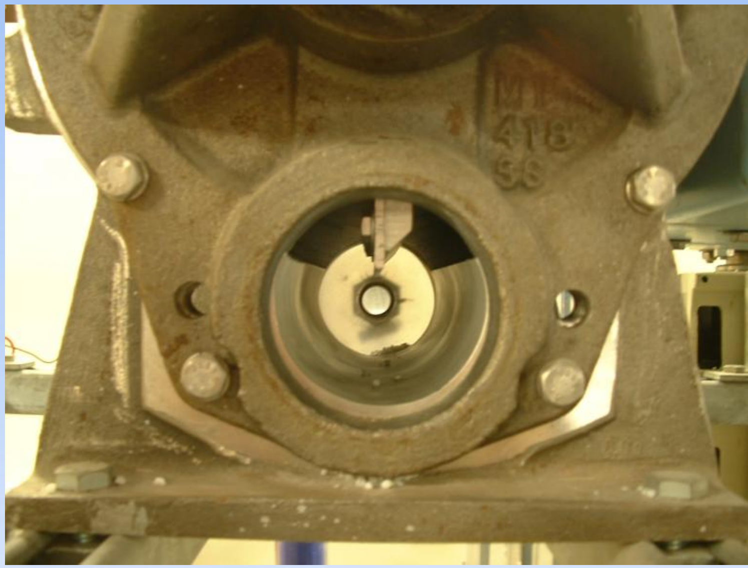
Core region: r/R<0.7; boundary region: 0.8<r/R<1.

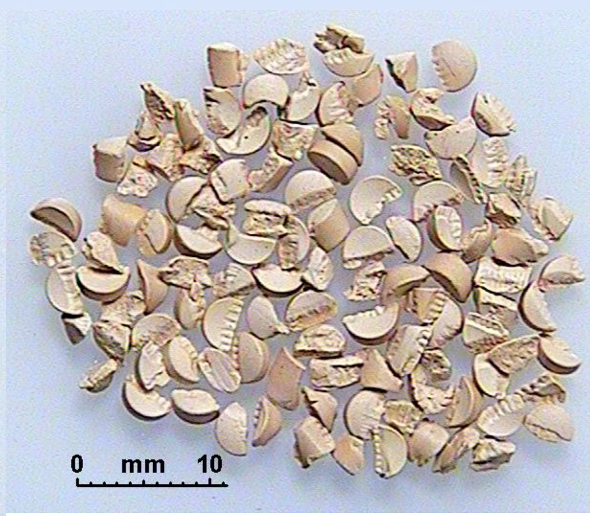
Lower air flow rates give rise to half-ring and ring flows. Fluid drag forces within the wall boundary layer are reduced to the same order of magnitude as that of gravitational forces. A dynamic equilibrium may be established between the two types of forces.

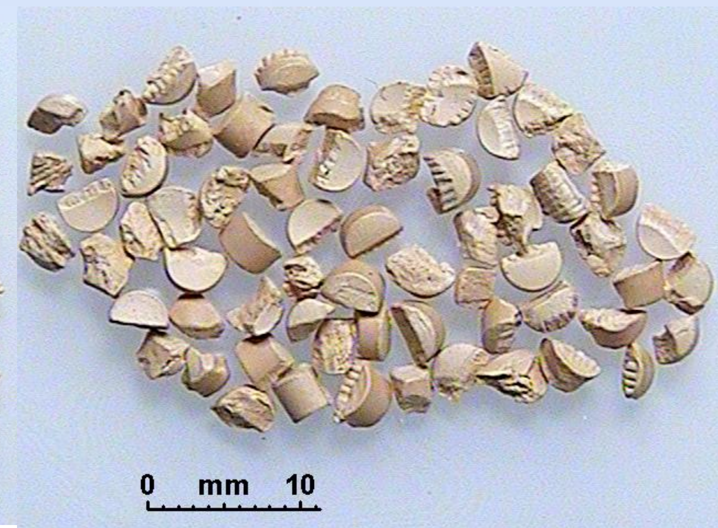
Electrostatic force may then emerge as the dominant factor affecting granule behavior.

Yao et al. 2006 *AIChE J*. 52, 3775-.

Granular attrition effect

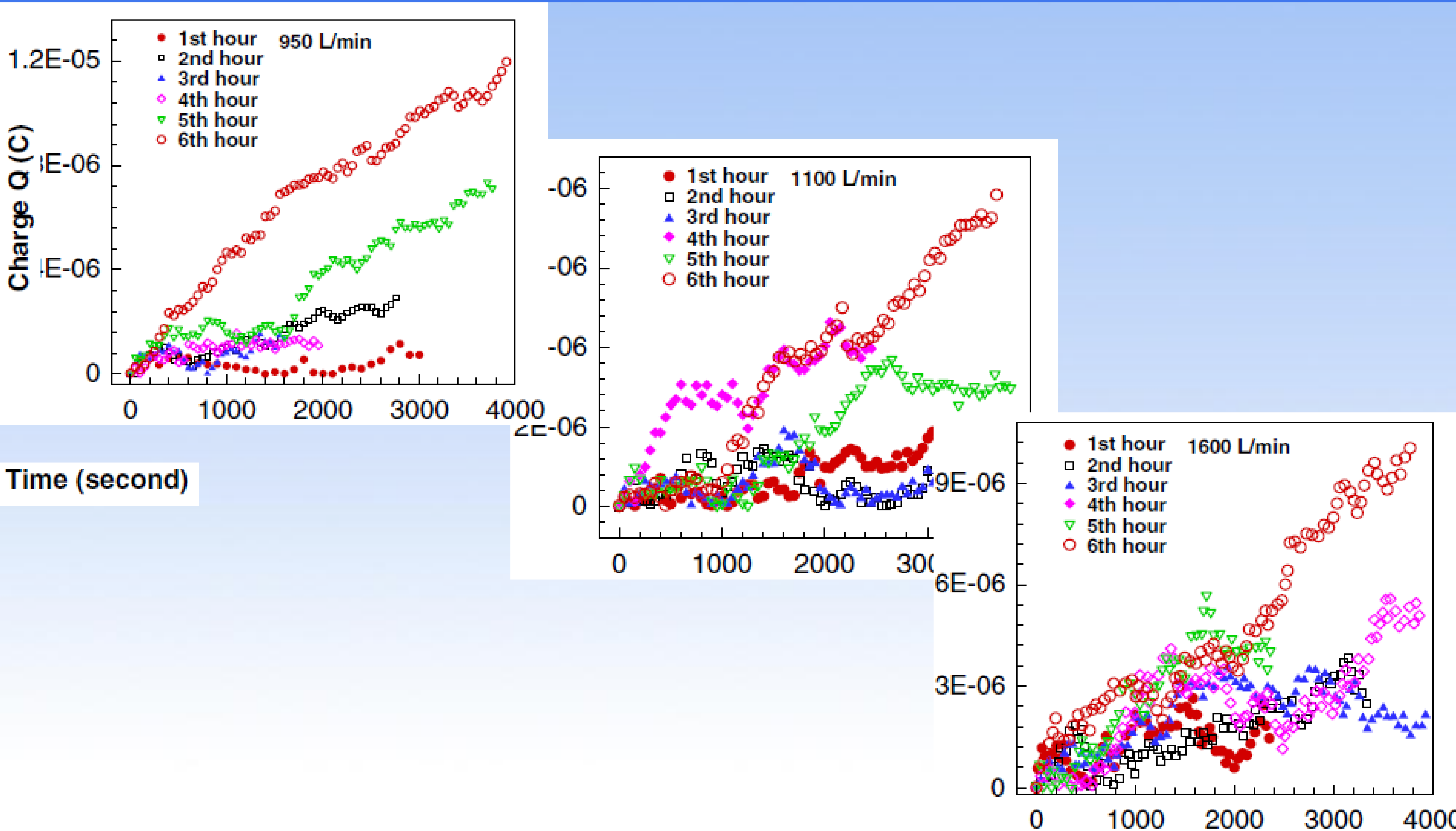




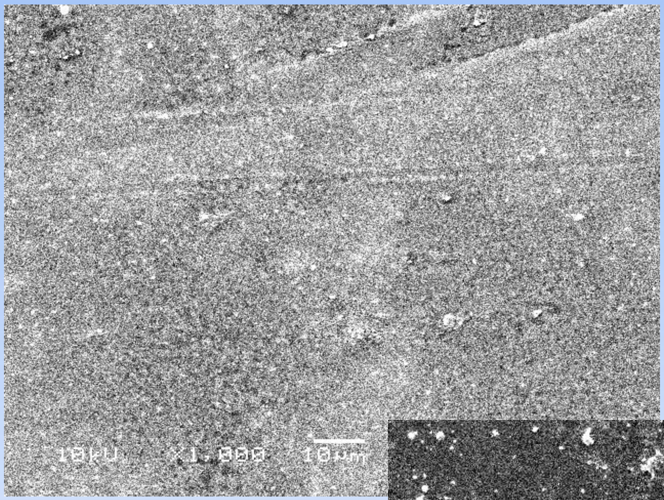


Yao et al. 2006. *Chem. Eng. Sci.* 61, 3858-

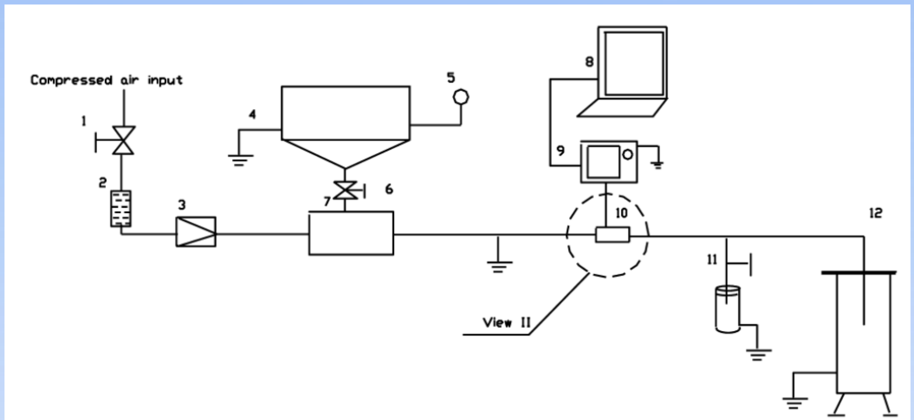
Granular electrostatics – attrition

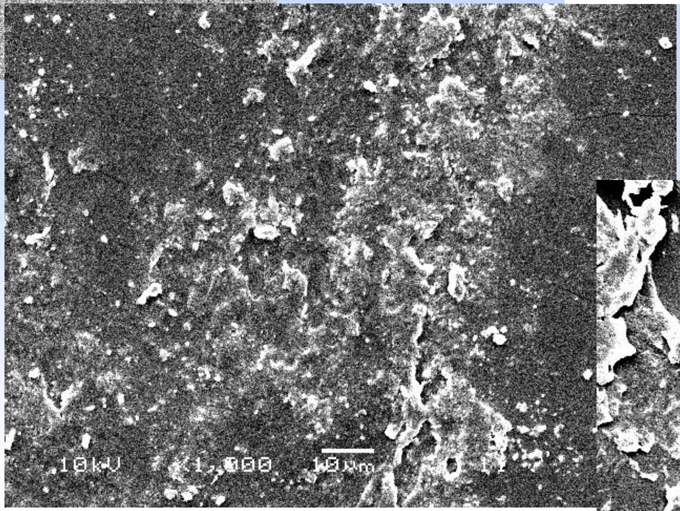


Charge generation mechanism
- tribroelectrification



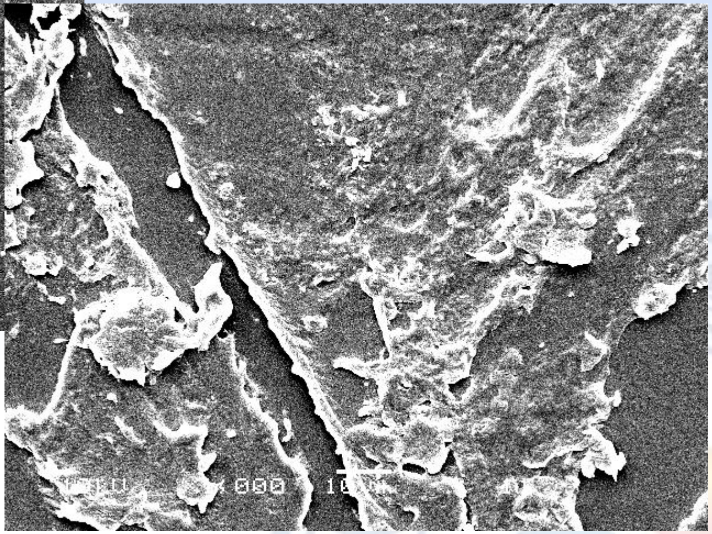
Fresh film



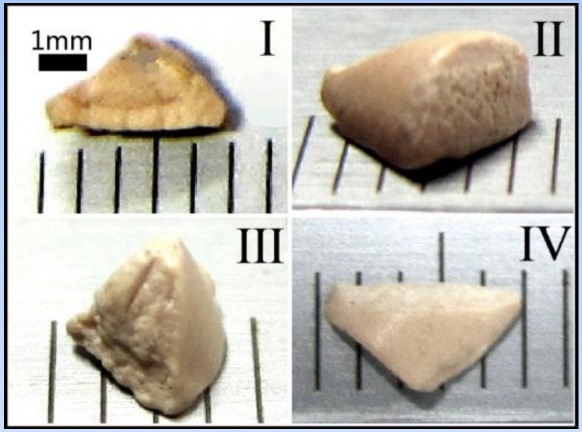


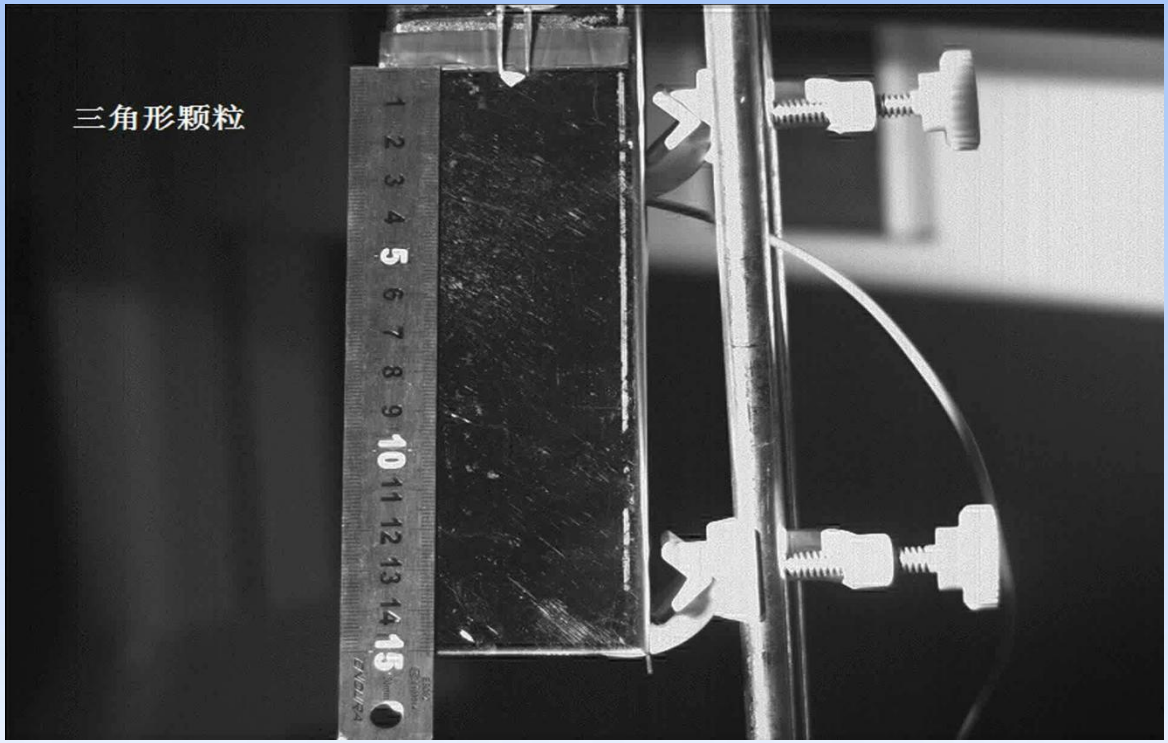
Used for 2 mins

Used for 10 mins



Single-granule test





Setup： **Faraday cage** (TR8031, Advantest Corporation, Japan)

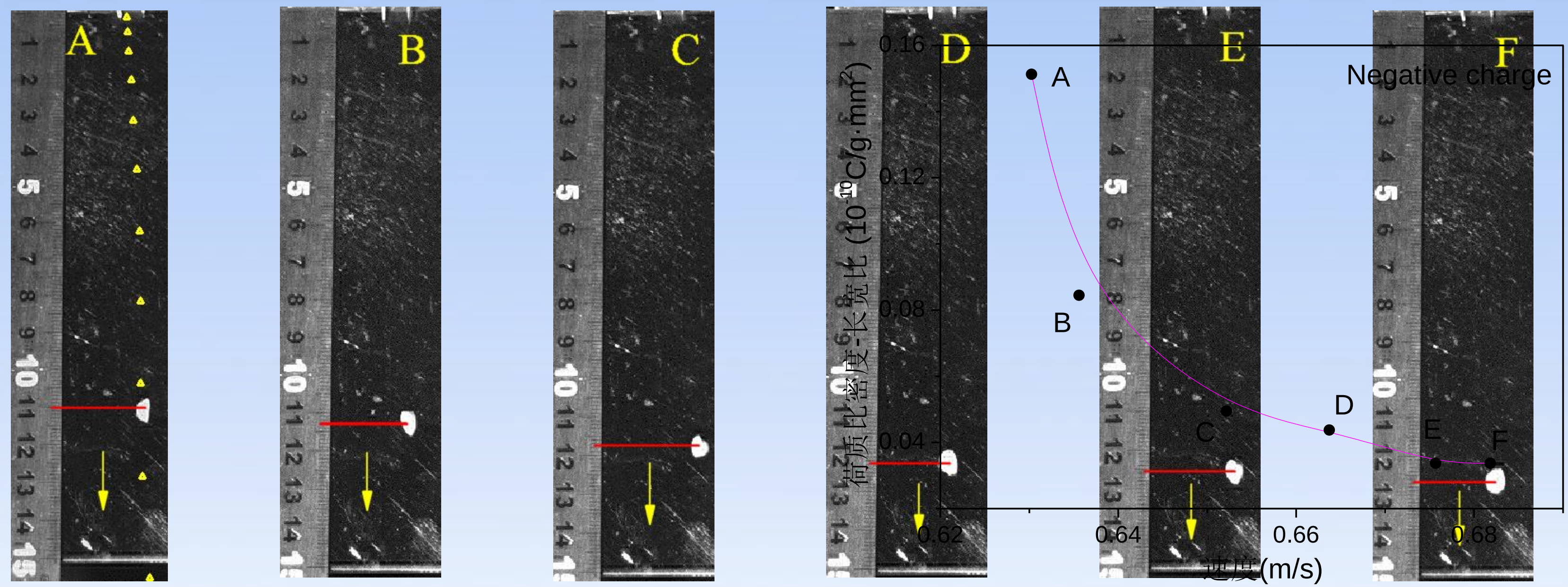
Electrometer(Advantest R8252 Digital Electrometer, Advantest Corporation, Japan)

High-speed camera (Japan: OLYMPUS, i-speed LT)

Stainless steel : 15cm*5cm

Sliding velocity effect

T= 0.2s

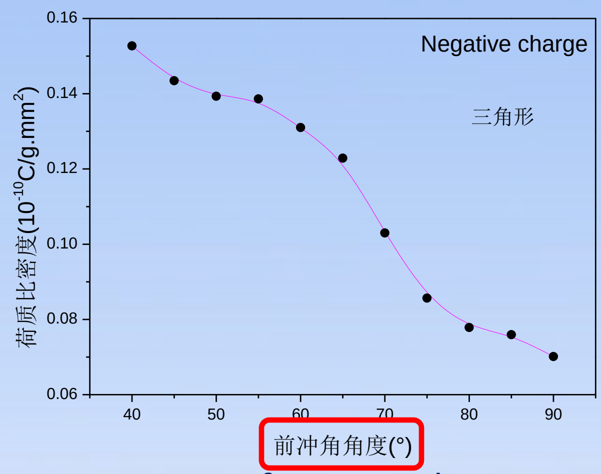


Time cost:

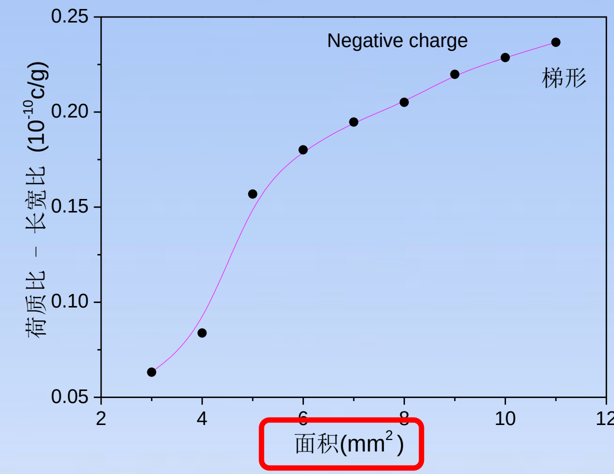
Electrostatics at corresponding point

0.238s 0.236s 0.230s 0.226s 0.222s 0.220s

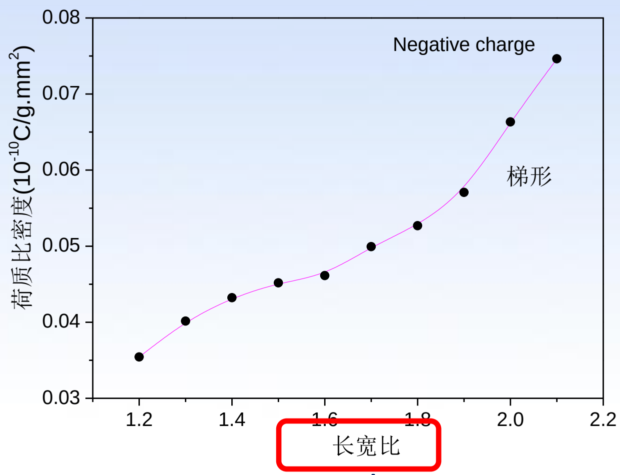
Granular shape effect



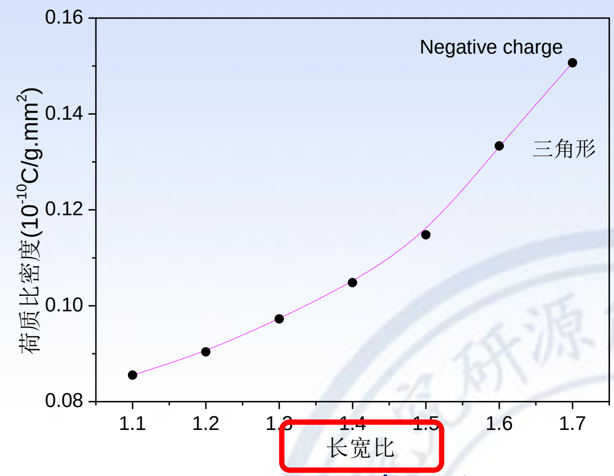
Front-facing angle



Area



Length ratio



Length ratio

Conclusions

- In the granular conveying system, air flow rate is a key factor determining the electrostatic behavior of granular flow. The lower the air flow rate, the higher the induced current and particle charge density. These in turn lead to particle clustering and the formation of such structures as half-ring and ring in the vertical conveying pipe.

- The electrostatics of granular flow in a pneumatic conveying system was quantitatively characterised by induced current, particle charge density and equivalent current of the charged granular flow and found to increase with granular attrition occurring in the rotary valve. A new method using granule size and shape is proposed as a useful tool for characterisation of electrostatics in general systems where granules are made up of complex combinations of different sizes and geometries.

- Granular size/shape due to attrition is found to affect electrostatic charge generation characteristics. It was found that some factors, such as granular front-facing angle, length-ratio, sliding direction, sliding times and environmental relative humidity, had significant effects on granular electrostatics generation.

- The mechanism of electrostatic charge generation for the granular flow in the pneumatic conveying system mainly depends on tribroelectrification due to strong force effect on the surface when the particles slide on the pipe wall.

Acknowledgements

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- ✓ This project is supported by
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